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CONSULTANT REPORT

Assessment of Piezoelectric Materials for Roadway Energy Harvesting

Cost of Energy and Demonstration Roadmap

Prepared for: **California Energy Commission**

Prepared by: **DNV KEMA Energy & Sustainability**

JANUARY 2013

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PREFACE

The Energy Commission seeks to better understand the current status of piezoelectric-based energy-harvesting technology as applied to the generation of electricity from roadway and railway applications. Over the past few years, considerable information has surfaced on these uses of piezoelectric-based energy-harvesting technology. There is a need to obtain a third party independent assessment of the available information and to determine if a specific future evaluation or demonstration will facilitate the commercial success of the technology. One area of interest is to determine if the technology has the potential to generate electricity with performance, reliability, and cost projections that are comparable to existing or emerging renewable energy sources.

The Energy Commission and DNV KEMA Energy and Sustainability (the Contractor) have collaborated with the California Department of Transportation (Caltrans) and with California Assemblyman Michael Gatto's office to complete these activities. If the results of this study indicate that a field demonstration is feasible or desired, the Energy Commission will work with Caltrans to conduct future research and demonstration projects that meet or exceed all required standards and regulations for California roadways and railways.

The objective of this report is to provide an independent assessment of the commercial status and future potential of piezoelectric-based energy-harvesting technology as applied to the generation of electricity from roadways. Information is provided about railway applications where available. This report describes the original purpose, approach, results, and conclusions of the evaluation. A presentation of any available project, laboratory, or field demonstration data published on energy generated by piezoelectric transducers under roadways or railways is included.

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ABSTRACT

Piezoelectric materials for the purpose of harvesting energy from roadways are discussed. A literature review of recent demonstrations and applicable technologies is provided, and a summary of relevant data is extracted from the literature. The data is used for inputs into a cost model to examine the minimum cost and performance metrics which are needed to calculate a levelized cost of energy over the estimated lifetime of the piezoelectric roadway system. The cost of energy is computed using vendor-supplied information. However, simplified traffic models are used to cross-check vendor claims and determine which factors contribute to uncertainty about the cost of energy.

Keywords: Piezoelectric, energy harvesting, waste vibration, highway

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EXECUTIVE SUMMARY

The details of this report entail a description of the present state of the art in piezoelectric materials, an assessment of the present demonstration data available, and a technoeconomic analysis of that data to assess the cost of energy for piezoelectric energy harvesters in roadways.

It was found that:

- Three vendors were reviewed. The vendor-based Levelized Cost of Energy (LCOE) ranges from $0.03-$0.18/kWh for compression-based systems. The mean of this range is $0.11/kWh. Vibration-based systems claim $0.06-$0.08/kWh. DNV KEMA estimates the actual cost of energy to be between $0.07-$0.20/kWh with 90 percent of values at $0.20/kWh or less for roadway piezoelectric energy harvesting technologies, provided that installed nameplate power densities > 300W/ft^2 are possible.

- A simple traffic model was constructed to validate vendor claims. It was found that some performance metrics appear to be mutually exclusive; therefore, further validation of the power output is needed to substantiate vendor claims. Power output per module is an objective metric that should be used for comparative evaluation.

- The three most important factors that determine the cost effectiveness of the piezoelectric roadway energy harvesting system are: (1) power output per installed module, (2) lifetime of the system, and (3) total installed cost. The first factor comprises power density and traffic flow rate. System power output is dependent on vehicle weight and power pulse duration.

- Power density is increased by means of novel, high density packing of materials and mechanical design. Systems are best utilized in high traffic flow rates. Parameters such as vehicle weight and power pulse duration are location-dependent; yet they are critical to system economics.

- The technology is in early stages of product development. Most vendors quote system level metrics – such as kW/km – which contain contingency data that is difficult to compare across regions. Public demonstrations to date lack data for commercial designs.

- Due to the intermittency of the power generated, there is a need for energy storage or net metering. Only one vendor of the three evaluated acknowledges energy storage costs.

- Further consideration of railways is needed. The installed cost of railway harvesters is likely less than roadway harvesters, and overall efficiency and cost of energy can be reduced in this application. However, there is little public data on railway installation at this point in time.

- In the event of an independent evaluation, the assessment should include:
    - Independent verification of power output per module.
    - Lifetime and durability as a function of uneven wear in the system, and downtime associated with failing modules, maintenance, and replacement.

- Installation methods, downtime associated with installation, and maintenance of the system as well as verification of other balance of system (BOS) costs such as energy storage or net metering.
- Added value and monetization of additional data extracted from the piezoelectric system, value of avoided inspection costs for the roadway or railway, if any.

CHAPTER 1: Basics of Piezoelectric Materials

What are Piezoelectric Materials?

Simply stated, piezoelectric materials are crystals that generate electricity when compressed or vibrated. They have the unique opposite property of generating a stress when voltage is applied to them.

Piezoelectric materials fall within a class of multiple solid state materials that can generate electricity with the application of some stimulus such as heat, stress, or light. Photovoltaic materials generate electricity with the application of light (the basis of solar panels), and thermoelectric materials generate electricity with the application of heat. Piezoelectric materials generate electricity with the application of stress. These materials are all semiconductors, meaning they are much like conventional electronics, generally constructed of Silicon (Si) or Germanium (Ge) with additional elements.

Using piezoelectrics to harvest vibration energy from humans walking, machinery vibrating, or cars moving on a roadway is an area of great interest, because this vibration energy is otherwise untapped. Since movement is everywhere, the ability to capture this energy cheaply would be a significant advancement toward greater efficiency and cleaner energy production.

Benefits of Energy Harvesting

The topic of energy harvesting generally refers to the capture and storage or direct use of ambient energy for human purposes. As solar panels *harvest* the energy contained in sunlight and convert it to electrical energy, other forms of energy harvesting also capture ambient energy, usually in the form of vibration or heat, and convert it to a useful energy medium such as mechanical or electrical energy.

Energy harvesting may or may not capture renewable energy. In the case of sunlight, the energy is renewable because it is sourced from the sun, a source of nearly infinite energy for the planet and the solar system. Waste heat in an industrial facility may not be renewable since the processes generating the waste heat may not be renewable, however, waste heat may be a significant source of energy to be harvested. Generally, the term *renewable* tends to be paired as *inexhaustible* in the context of energy, so the classification of harvested energy depends on this definition. In the sense that all processes are inherently inefficient (as stated in the second law of thermodynamics), there is theoretically an inexhaustible supply of waste energy and fractions of it may be harvested from inefficient processes.

Generally, if waste energy in a system is harvested, the overall efficiency of the system is increased. Waste vibration energy may come from rotating machinery, manufacturing processes with hydraulic machinery presses, conveyor belts, electric motors, or engines which may or may not be fueled by renewable energy. In this case of this study, waste vibration energy in roadways is the desired energy to be harvested.

The subject of this investigation is to examine the harvesting of energy from California roadways. Information about railways is sparse, but it is provided within this report if it is available. Vehicles driving along the highway or city street generate vibration as the vehicle tread encounters the texture of the pavement and the vehicle suspension undulates from variations in height along the roadway. The kinetic energy contained in these movements goes unused on a system level, although these processes are part of the physics in creating a comfortable and functional ride in a vehicle and maintaining traction. The main source of energy in a piezoelectric highway energy harvesting event is the impact of the vehicle tire (and the weight it bears) as it transitions over a piezoelectric device. This energy is kinetic energy that goes otherwise unused, and is an accepted inefficiency that comes with the use of vehicles as a transportation mode. Harvesting a fraction of this energy may be a source for increasing the overall efficiency of transportation infrastructure.

What are piezoelectric materials commonly used for?

The majority of literature for piezoelectric materials is directed toward vibration, ultrasonic sensors, and transducers. A piezoelectric device requires a stress to function, such as compression from outside forces. The first application of stress will generate voltage and current (power) within the material, but the stress must be relaxed in order for the material to generate power again. In this way, piezoelectric materials require alternating stress - or vibration - to function pseudo-continuously.

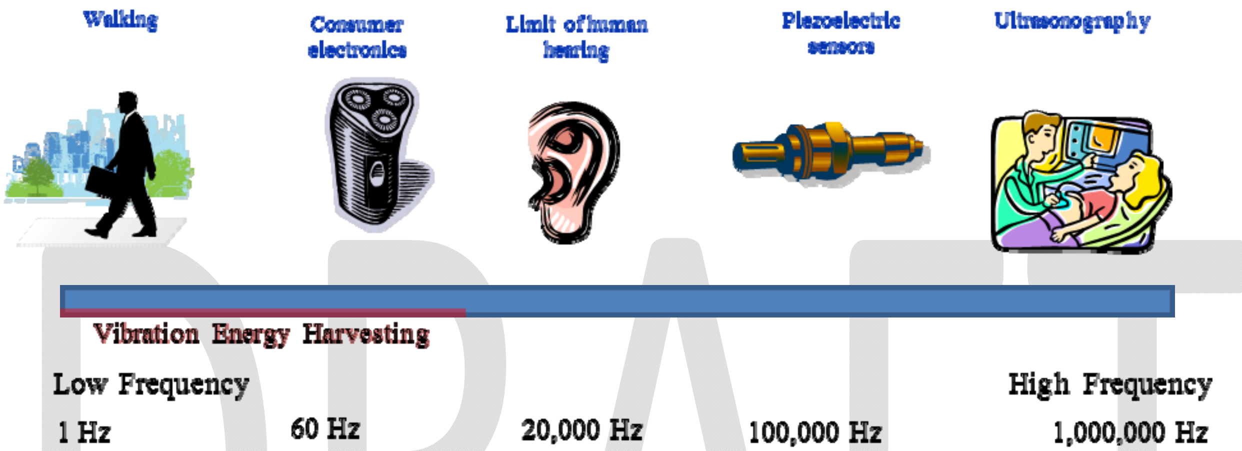
The field of acoustics deploys piezoelectric materials for a wide range of sensors and actuators. These sensors vibrate at very high frequencies above the range of human hearing which allows them to be very sensitive to micro-scale physical features. Ultrasonic acoustic piezoelectric transducers are often used to inspect welds in pipelines, for example, to look for voids, cracks, or other defects that might make the weld incapable of holding pressure. In the context of energy harvesting, piezoelectrics are often considered as small-scale energy harvesting sources to power a sensor network or sensor array.

For the purpose of energy harvesting, the vibration frequencies are typically much lower than what is required for ultrasonics. Recall that piezoelectric materials can be stressed or compressed to create current, or current can be applied to generate a stress. A human walking, for example is a low frequency event that can be captured in the form of stress on a piezoelectric platform. A person walking across a room may complete 1-2 steps per second. Each step introduces a stress in the floor of the room, and the frequency of that alternating stress would be about 1-2 vibrations per second, and this waste vibrational energy can be harvested.

Vibrations per second are a measure of frequency, often stated in Hertz (Hz). One vibration per second is equal to 1 Hz. Two vibrations per second are equal to 2 Hz. The common United States household's electrical circuit carries electricity oscillating at 60 cycles per second, or 60 Hz, which is evidenced by the low frequency buzz of an electric shaver. An ultrasonic sensor, however, may vibrate at thousands or tens of thousands of cycles per second and this may be above the range of human hearing which ranges from 20 Hz to 20,000 Hz. Ultrasonics vibrate above the human range of hearing, as high as 100,000 Hz. One of the most common ultrasonic technologies that most people experience is the *ultrasound* used to image unborn babies in the womb. The scan is performed by an ultrasonic device which processes reflection of the sound waves to produce an image of the baby. This ultrasound equipment operates around 1 million Hz to 18 million Hz (MHz). The range of these frequencies is illustrated in Figure 1.

Why is frequency important? One needs to understand that the type of piezoelectric that best harvests energy should have a frequency response suitable for the vibration. Piezoelectrics designed for ultrasonics would have very little success if they were put into an application to harvest energy from walking. They would also likely be too expensive. The piezoelectric materials relevant to this application are design for low frequency vibration harvesting in the range of 100-120 Hz[1].

Figure 1: Energy Harvesting of Vibrations is Possible Typically in the Lower Frequency Range from 1-1,000 Hz



Source: DNV KEMA Energy and Sustainability

Harvesting the vibration energy from humans walking has been a past target of piezoelectrics. There have been studies focused on future energy efficient cities that have solar panels on the rooftops of buildings and piezoelectrics in the sidewalks to harvest energy from foot traffic.

What are some relevant cost and energy metrics?

To determine how much energy piezoelectrics can produce, a few metrics need to be defined that will be useful for the discussion.

The first metric is **power**. Power is defined in Watts (W), which is defined as units of energy per second. Power is an indication of how quickly energy can be delivered. A powerful air conditioner can cool a room quickly, whereas a weakly powered heater may require a long time to heat a room. Other examples include a solar panel which may be rated at 200 W in peak sunlight at noon in the middle of a summer California day. A natural gas power plant may produce as much as 200 million watts (megawatts, or MW) to power a city and its surrounding neighborhoods, one million times more powerful than a single solar panel.

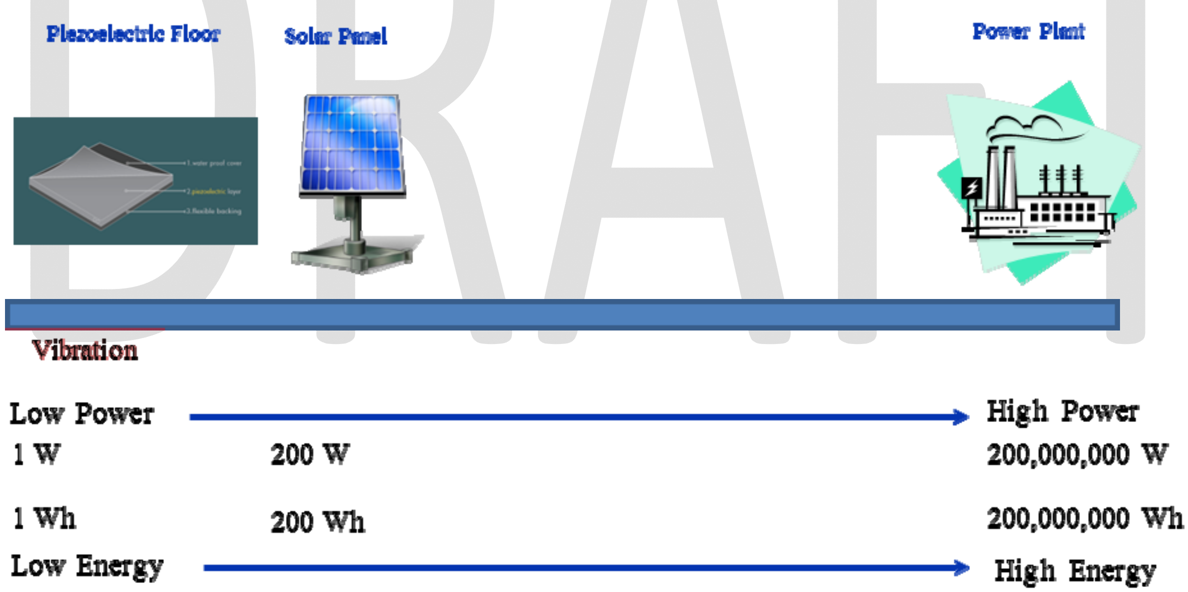
The second metric is **energy**. Energy is defined in many units. In standard units, energy is stated in Joules (J), but for electricity it is often most useful to define energy in terms of watt-hours (Wh), for example, how many watts are produced in an hour. In the examples above, the

[1] Cook-Chennault. "Piezoelectric Energy Harvesting: A Green and Clean Alternative for Sustained Power Production." Bulletin of Science, Technology, & Society, Vol 28, No 6 Dec 2008 pp 496-509.

solar panel would produce 200 Wh from noon to 1 PM. The natural gas power plant would produce 200 million watt-hours (200 megawatt-hours, or MWh) in the same hour. Again, the two examples are different by a factor of one million.

When discussing power and energy systems, it is helpful to talk about how much power or energy can be made within a footprint (area) or box (volume). These are stated as metrics such as power density and energy density. For systems that are flat like solar panels, power density might be in units of watts per square foot (or square meter). Consider the solar panel example from above, producing 200 W or 200 Wh in an hour. A typical solar panel might measure 2 ft x 3 ft, or six square ft (6 ft^2). Its power density would then be 200 watts in six square feet, or $200/6=33 W/ft^2$. The natural gas power plant might occupy a space of 100,000 square feet, perhaps fenced off in a remote place outside of the city. Its power density would be 200 million watts in 100,000 square feet, or 2,000 W/ft^2. Similarly, the energy density of these systems is 33 Wh/ft^2 for the solar panel and 2,000 Wh/ft^2 for the power plant. These metrics are described on a scale bar in Figure 2 below.

Figure 2: Power and Energy Scale for Piezoelectrics, Photovoltaics, and Conventional Power



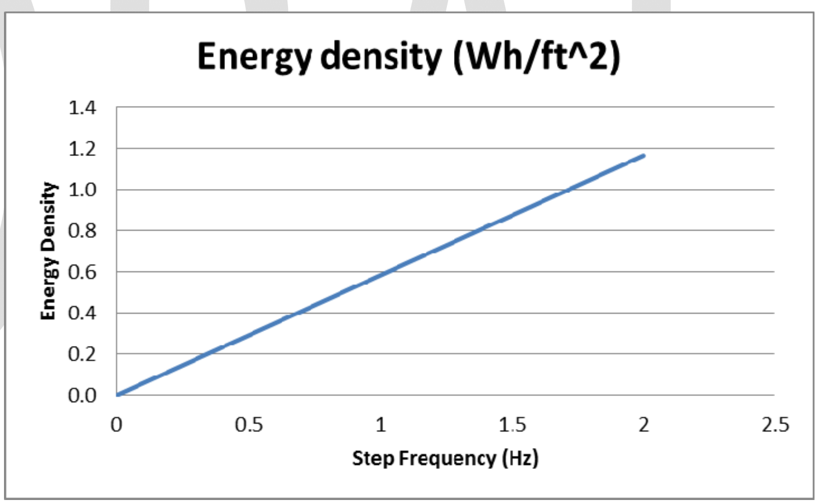
Source: DNV KEMA Energy and Sustainability

These numbers become interesting when applied to piezoelectrics, particularly in power and energy density. Consider the Digital Safari Greenbiz Company product. It estimates that a 3x5 feet panel will generate 17.5 watts per step. Human foot traffic over this panel occurs at approximately two steps per second (2 Hz). But note that the power output is not continuous, because power is generated only when a human steps on the panel. The power density of the flooring product is 17.5 W per 15 ft^2, or 1.2 W/ft^2, about 30 times smaller than a solar panel. The energy density is different because it depends on how often people are stepping on the panel. At best there is nearly continuous foot traffic on the panel resulting in a nearly continuous 17.5

W generated which would result in 17.5 Wh every hour, or an energy density of 1.2 Wh/ft^2. Therefore 17.5 W is the maximum power the panel generates, and it will be less if foot traffic is less. In fact, energy density is linearly proportional to the foot traffic, as shown in Figure 3. The same rule applies to a solar panel; its energy density varies with sunlight and it has zero energy density at night.

A third metric worth discussing is **capacity factor.** The relationship of traffic volume to capacity factor is important for the consideration of power output for a roadway energy harvesting system. Power equipment usually has a nameplate rating like the gas turbine mentioned above, such as a 1.5 MW wind turbine, a 200 Watt solar panel, or a 100 kW gas microturbine. These nameplate ratings carry unspoken qualifiers associated with peak output and have an impact on the energy generated. In reality, the wind turbine likely spins about 30 percent of the time when wind conditions are favorable. Therefore, it may be rated at 1.5MW, but this does not mean it produces 1.5 MWh per hour. Instead, it produces 0.3*1.5MWh/h, or about 0.5 MWh/h. The fraction of time that the power equipment produces power is the capacity factor.

Figure 3: Power and Energy Density Depends on Foot Traffic for the Piezoelectric Floor



Source: DNV KEMA Energy & Sustainability

The lesson learned from Figure 3 applies to a roadway model also, and immediately implies that an energy harvesting system will benefit the most from roads with high traffic volumes in the same way that a piezoelectric floor will benefit from high foot traffic. A major focus of past research and an essential part of any United States based demonstrations will be a study of energy production versus traffic volume, average vehicle speed, and even vehicle weight. This will be explained further in Chapter 3: Conclusions and Recommendations. Energy and power density is expressed by vendors in terms of kWh/km and kW/km, respectively. However, it is also useful to discuss power density in terms of W/module or W/ft^2 of devices.

The cost of these systems is disparate across the literature, but two cost metrics are of use. Floor-based piezo energy harvesting systems such as those advertised by Piezo Power use a Rochelle salt panel measuring 1500 ft^2 in area for $2,250, or $1.50/$ft^2$ [2]. The Innowattech roadway system has been quoted to cost $650,000 for the installation of one km of roadway, which generates 100 kW. This corresponds to an overnight capital cost[3] of $6,500/kW. These two technologies place a wide range on the cost per square foot and this can be attributed to the installation needs. Innowattech has optimistically stated in press releases that the installed cost can be cut by two-thirds.

Efficiencies of piezoelectric materials can range from 20-30 percent for some devices and as low as 10-15 percent for low cost devices. These roadway piezoelectric devices are engineered toward low cost and therefore have efficiency at the lower end of the spectrum.

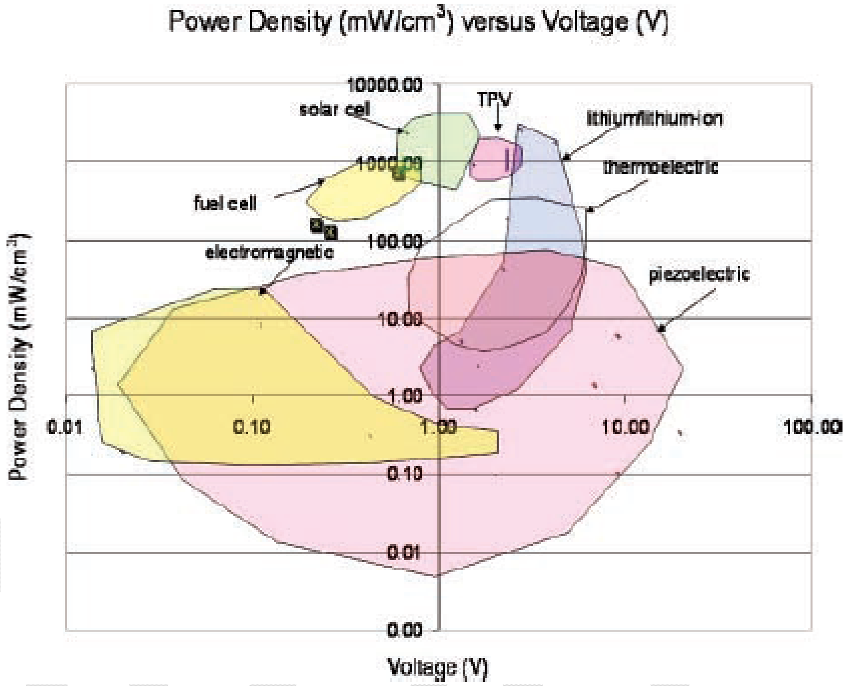
Because the application of piezoelectric materials as bulk-energy producing devices has only recently been demonstrated, there is a wide range of literature concerning power and energy density characteristics of these materials. Some materials are likely better suited for micro-harvesting applications (such as in sensor networks) while others are more suitable for bulk power harvesting and production. As can be seen in Figure 4, piezoelectric devices can be compared to the power density of Li-batteries in some cases, but the range of power densities is quite large[4]. This illuminates the fact that the technical database on these materials is large and diverse and therefore a study of their application toward roadways requires a focused study of the specific materials and devices available.

[2] Walsh, et al. "Piezo Power." Digital Safari Greenbizz Company Business Plan Competition, 2011.

[3] "Overnight" capital cost is an estimate for the materials and installation for energy systems, and does not include the sometimes immeasurable costs of permitting, construction delays, and other delays which add to the cost of construction projects that are specific to the location, the contractors, and the technology. Overnight costs are a generally accepted comparison for energy systems and are often quoted in this fashion in DOE, EIA, and IEA documents.

[4] Cook-Chennault. "Piezoelectric Energy Harvesting: A Green and Clean Alternative for Sustained Power Production." Bulletin of Science, Technology, & Society, Vol 28, No 6 Dec 2008 pp 496-509.

Figure 4: Piezoelectric Devices have Voltage and Power Capability Similar to Li-ion Batteries



Source: Cook-Chennault, et al[5].

Two Ways to Harvest Energy with Piezoelectric Materials

As mentioned above in the section titled "What are Piezoelectric Materials?", a piezoelectric material generates energy when it is stressed and strained. This primary mechanical stress generates a voltage and current pulse, the product of which is power (Watts). The details of roadway piezoelectric energy harvesting systems are given in Appendix A on page 54.

There are two technologies reviewed in this report that harvest energy in two different ways, but both rely on stressing a piezoelectric element. In the first case, a stack of piezoelectric materials is compressed to generate energy and a pulse of power is registered with each compression cycle (such as the passage of a vehicle tire over the stack). In the second case – based on what can be simplified and inferred from product literature – the energy harvesting mechanism appears to be an array of cantilever or bent beam piezoelectric energy harvesters vibrating as a result of external stimulus (such as the passage of a vehicle tire overhead). The power profile continues to generate power for a longer duration as the vibrations decay. An example of a vibrating device is shown in Figure 5 in comparison to a compression-based energy harvesting device.

An array of many devices within a small volume leads to higher energy or power density. However, the array configuration and duration of output will determine these properties.

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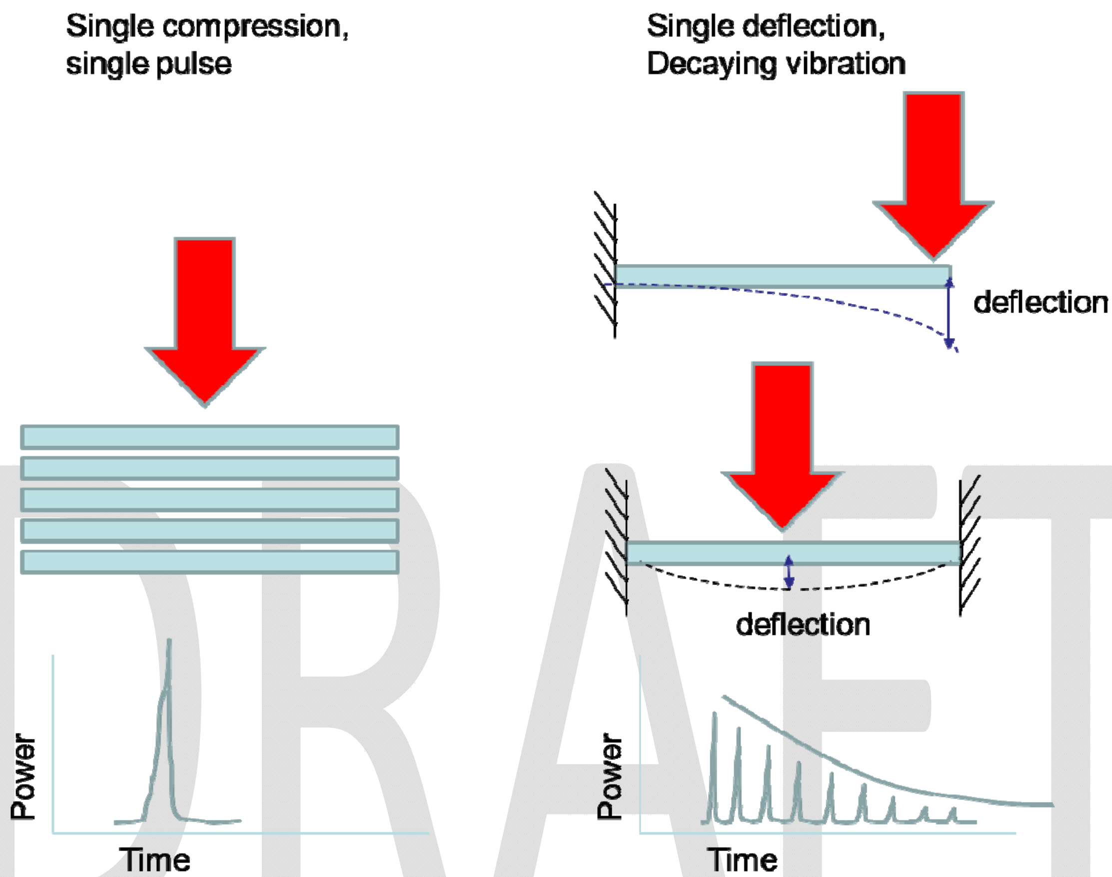
[5] Cook-Chennault. "Piezoelectric Energy Harvesting: A Green and Clean Alternative for Sustained Power Production." Bulletin of Science, Technology, & Society, Vol 28, No 6 Dec 2008 pp 496-509.

Figure 5: Difference in Performance Characteristics of Compression-based Energy Harvesters and Cantilever Energy Harvesters



Energy Density of a Compression-based System

A critical assessment of the compression mechanism for harvesting energy was provided by University of California, Berkeley[6]. The calculation explains with mathematical justification that simple compression of a given volume of space does not itself actualize significant energy. However, the calculation neglects engineering innovations in the piezoelectric module which can increase energy density and amplify the effect. This is highlighted by a demonstration from Virginia Tech, which uses a lab-designed, simplified piezoelectric power module that generates 100 times more power than what Berkeley concluded is possible without any significant engineering other than optimized placement of stacks.

Berkeley calculated that the maximum amount of energy imparted during a compression of 0.08 m (3″) is 6.6 x10^{-5} J (less than 1 mW). Virginia Tech has built a prototype energy harvester that is explained in detail in Appendix A, page 54. The Virginia Tech prototype energy harvester has demonstrated an output of 0.08-0.14 W from the same footprint, so there is a discrepancy in what Berkeley has calculated versus what is possible. Some of this discrepancy is in the

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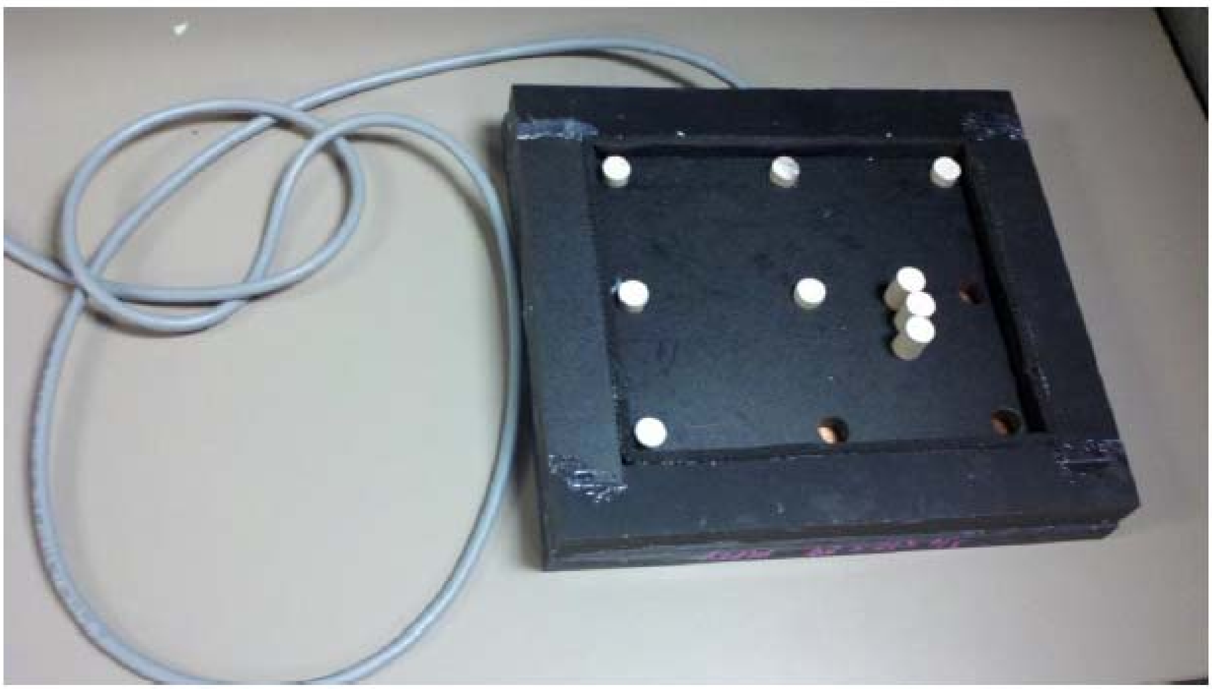
[6] Waterbury, Wright.

assumptions for the calculation, and other sources of discrepancy arise from failure to acknowledge engineering modifications to increase power density. Commercial compression-based energy harvesters contain mechanical linkages to multiply forces that increase their power density. Virginia Tech modeled a plate-over-pillar design to distribute load across small piezoelectric stacks (Figure 6), which has inherently lower energy density than what is implied by commercial designs. The Virginia Tech unit does not include any force-multiplying mechanism or lever configuration, yet it has demonstrated greater power output than what Berkeley calculated.

Figure 6: Configuration of Stacks in the Virginia Tech Piezoelectric Harvester



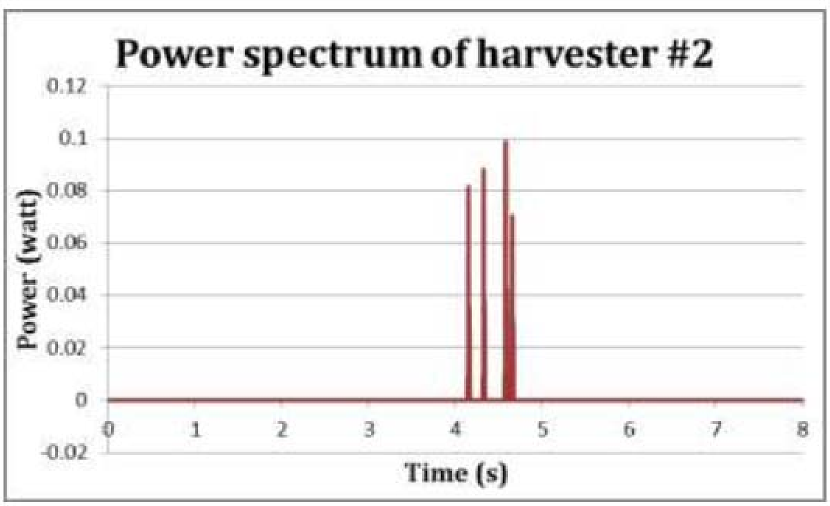
The target trucks in the Virginia Tech study were tractor trailers which are a Class 8 weight rating at 33,000 pounds or more. Tractor trailers have five axles; two on the trailer, two rear axles on the tractor, and one front axle[7]. The characteristics of the Berkeley truck do not match any United States vehicle class, so the modified calculation uses Class 8 vehicles as the basis – which describes the same tractor trailers demonstrated in the Virginia Tech study. Using this estimate, the load should be increased per wheel to 14,700 N, or about five times the Berkeley assumption. Using the five axle truck corrects the number of cycles to 2.9×10^7. Using the similar estimates for the dimensions of the harvesters and accounting for the corrections for weight and axles, the Berkeley calculation method yields about 0.01 kW/km rather than the 0.0018 kW/km that was estimated in the paper. Nevertheless, this is still much less than what vendors have claimed. It is also less than what has actually been demonstrated by Virginia Tech (Figure 7).

[7] Berkeley estimated 8 axles.

Data shared with Virginia Tech by Innowattech indicated that a 4 mm thick stack of 15 mm diameter could generate 0.25W with 64 percent efficiency at 100 MPa of load. This is equivalent to 64,516 N/in^2. When comparing Figure 7 and Figure 9, it can be seen that such loads are near expected vehicle loads at the tire. In terms of power density, this is 0.25W/.001 ft^2, or about 250W/ft^2. This is what is possible from the materials but it is acknowledged that this is not necessarily what is possible in practice. There are several inefficiencies involved in packaging and converting this power to useful energy. This data, in addition to what has been demonstrated by Virginia Tech, implies that it is possible to harvest power at levels higher than what Berkeley calculated.

The demonstration from Virginia Tech measured 0.08-0.14 W for a single compression event (example in Figure 7) which is 100x larger than the ~1 mW output calculated by Berkeley. Within a 1 km stretch of highway, the wheel base and shadow footprint of the vehicles occupying the space will determine how many devices can be simultaneously stimulated. Because the compressive-based energy harvesters generate power in sharp, discrete pulses, there is very little overlap between excited harvesters and inactive harvesters (see "Effect of Wheelbase on Capacity Factor"). The comparison between the Berkeley calculation, the corrected estimate using United States tractor trailers as the basis, and the Virginia Tech demonstration is shown in Table 1.

Figure 7: Power Output from a Single Innowattech Energy Harvester during the Virginia Tech Demonstration



Source: Virginia Tech

Table 1: Comparison of Calculation Results across Multiple Third Party Investigators into the Compression-based Energy Harvesting Technology

Berkeley Result	Modified Berkeley Calculation	Virginia Tech Demonstration
600 trucks per hour	600 trucks per hour	As low as 167vehicles per hour

Berkeley Result	Modified Berkeley Calculation	Virginia Tech Demonstration
45,000 N truck weight (10,0000 lbs)	147,000 N truck weight, tractor trailer (33,000 lbs, Class 8)	Tractor Trailer
8 axles per truck	Tractor trailer, 5 axles	5 axles
0.0018 kW/km output, < 1 mW at the module	0.01 kW/km, 0.017 W/module	0.08-0.14 W per module

The Berkeley critique makes a compelling argument to show that energy density is a challenge for this technology, but it ignores engineering innovation on mechanisms to maximize power density. In the same way that photovoltaic (PV) systems can employ mirrors and lenses to concentrate light on active modules, the piezoelectric modules can use mechanical advantage and novel packing of materials to the same effect. While conservative, the demonstration data shows that more is possible than what Berkeley calculated, yet not enough to be financially compelling with a simple design. Commercial designs are further along in the product development cycle than the Virginia Tech design, and have presumably overcome some of these challenges. Therefore, there is reason to show careful consideration to investment in demonstration while accounting for the novel aspects of commercial products. It is proposed in in the recommendations that if an evaluation path is chosen, it be managed in a staged gate fashion to minimize risk and investment in an R&D endeavor by first performing independent tests of commercial power modules to verify their claimed output. Any evaluation should start –at a minimum – with a laboratory independent confirmation of the module power output from each of the vendors. Such testing can validate claims without asking vendors to reveal their intellectual property, as well as conservatively address the concern embodied in the Berkeley calculation.

Effect of Wheelbase on Capacity Factor on kW/km

Recall the discussion of capacity factor on page **Error! Bookmark not defined.**. The main take away from the capacity factor discussion is this: because the piezoelectric system is distributed over a wide area (for example, a 1 km strip of roadway), the system is challenged to be 100 percent active, although it is unlikely that all modules can be generating at the same time. In order to understand the factors that contribute to the capacity factor of a piezoelectric system, the Virginia Tech demo is used to consider a simple walkthrough of how the energy harvesting system works:

- A 1 km strip of highway sits empty. Imbedded in its pavement are two parallel rows of energy harvesters, each numbering 4900 units for a total of 9800 units. Each of them, when compressed, generates 0.1 W.
- A single truck comes from the distance and enters this 1 km strip of highway.
- As the set of wheels crosses the first two energy harvesters, a frozen frame snapshot in time reveals that each harvester generates 0.1W, for an additive power output of 0.2 W.
- As the first axles cross into the second row of energy harvesters, the next two harvesters are excited to produce 0.2W, and the first row is already relaxing to an uncompressed state. At this point, the net power output remains at 0.2 W.

- By the time the last axle of the truck has completely entered the piezoelectric envelope of the road, it will have five axles touching harvesters at any given time. If each unit generates 0.1 W, this means at any given time the truck is producing 1 W.
- The length of a typical tractor trailer is about 74 feet (888 inches). While this tractor trailer occupies space, no other vehicle shall occupy that space. The five axle wheelbase of a tractor trailer varies but it can be estimated at 68 feet.
- If the Virginia Tech devices are laid end-to-end and in contact with one another to maximize their density within the roadway, two rows of 111 units each can fit within the shadow of a tractor trailer. Within the shadow of the trailer, only 10 units out of 222 are being excited at any given time. Out of a potential 22 W (nameplate capacity), 1 W is being generated.

The thought experiment is illustrated in Figure 8 where it is shown that 10 energy harvesters are activated (shown in red) within the footprint of a tractor trailer. By this illustration, in one hour the nameplate capacity of the harvesters would indicate 22 Wh, but the net production would only be 1 Wh. This represents a capacity factor of 4.5 percent.

Within 1 kilometer, 44 trucks can fit if laid end to end. That means that within 1 km, 440 piezoelectric units are producing power out of 9800, or about 4.5 percent. The nameplate capacity of the 1 km strip would be 980W, but its actual output would be 44W, or less than an incandescent light bulb[8]. This is the minimum capacity factor limit.

Because the pulse of power in the compression-based piezoelectric unit is relatively fast (~0.1s), one might be able to imagine traffic traveling infinitely fast such that the duration between pulses would be so short that all units would be energized continuously. This implies that the harvesters should experience an impact at a minimum of every 0.1s in order to be nearly continuously *on*. Highway traffic speeds can induce a nearly constant active condition for the harvesters depending on speed and vehicle wheelbase. Given the length of the average 5 axle tractor trailer of 68 feet, for simplicity it may be assumed that an average distance between axles of 13.6 feet. A vehicle speed of 65 mph corresponds to 95 ft/s, which indicates that impacts occur on average every 0.13 seconds which begins to approach the power output duration. Recall in previous sections that frequency was defined in Hz. A power pulse every 0.13 seconds would correspond to a compression frequency of 7 Hz.

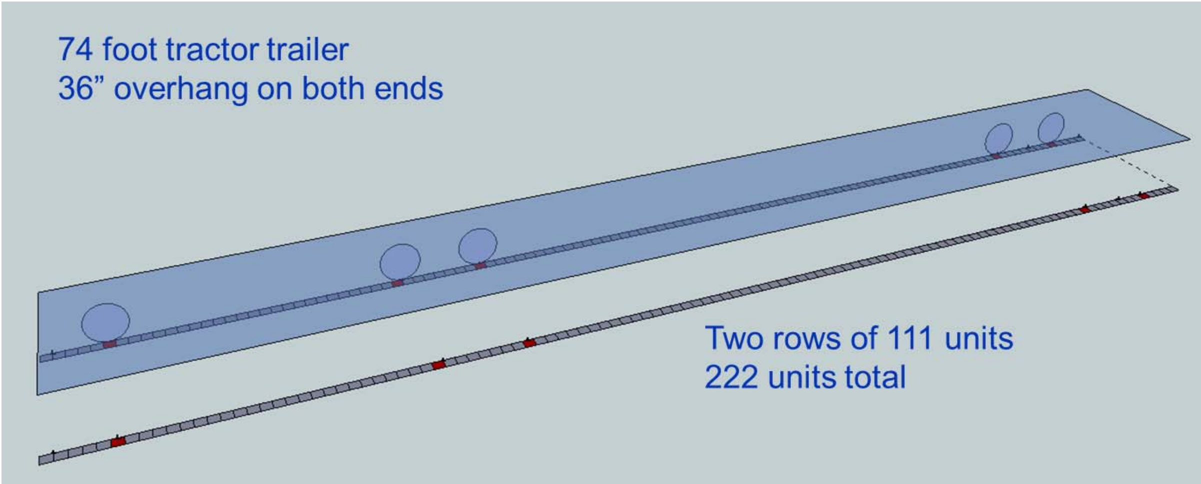
A continuous line of tractor trailers – connected at the bumpers - moving at 65 mph would produce a 0.1 s power pulse, followed by the remaining 0.03 second gap until the next tire impacts the unit producing another 0.1s power pulse. This idealized calculation would estimate a capacity factor of 0.1s/0.13s which is ~76 percent. In reality, traffic is not evenly spaced and the power delivery is not flat, and the density of tractor trailers is not perfect. As a rule of thumb, traffic tends to be spaced at least one to two vehicle lengths between each vehicle which indicates that only one out of every three spaces for vehicles are occupied (cutting maximum capacity factor estimates by 1/3). Therefore, one could see how capacity factors of ~20-30 percent may be possible in high speed and dense traffic. Nonetheless, the Virginia Tech demonstration illustrates a maximum limit of about 980 continuous watts, and estimating

[8] These assumptions are based on the Virginia Tech demo unit, which is prototypical and non-commercial and generates less power than what commercial products have claimed.

capacity factors of 4.5-50 percent correspond to a power output of 44-440 Watts/km. Note that this is watts – not kilowatts.

The last argument concerning capacity factor also illustrates how capacity factors for trains can be increased since trains are closely spaced. However there is downtime between trains. Piezoelectric systems on busy track lines would have maximized capacity factors.

Figure 8: Ten (red) out of 222 Piezoelectric Units can be Excited at Any Given Time with a Single Passing Tractor Trailer at Low Speeds



Source: DNV KEMA

The majority of vehicles on the road are not tractor trailers. Using information from the Transportation Energy Data Book[9], one can see that the majority of vehicles on the road are of the two axle vehicle (cars) and light duty truck varieties. Using the Virginia Tech data again as a standard output metric, if one assumes that a Class 8 tractor trailer generates a maximum of 0.14 W per wheel impact, one can scale the power output linearly with weight to estimate the net output per vehicle type[10]. Figure 10 reveals that those vehicles with the greatest energy harvesting potential are the fewest on the road. Of all vehicle miles travelled (VMT), trucks and busses comprise small fractions. Therefore, there is a need to place energy harvesters where they can be optimized for power output and capacity factor to take advantage of high traffic flow rates with a maximized cross section of heavy vehicles. This is perhaps the reason why Virginia Tech chose a truck weigh station on a highway, as it would target heavy vehicles while attempting to capture a high traffic flow rate.

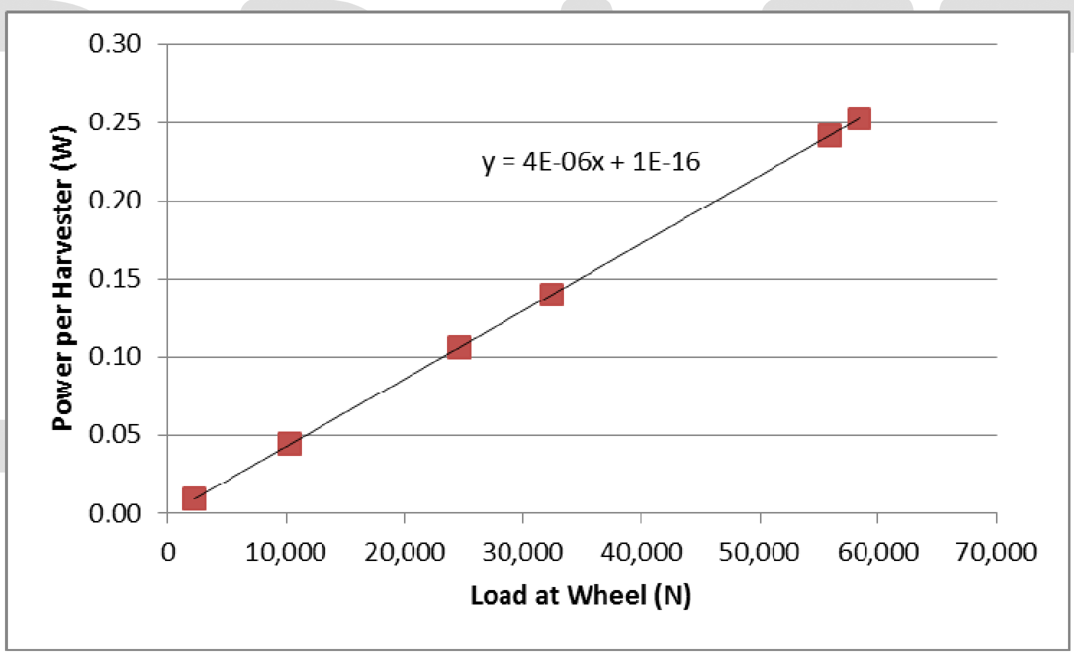
The estimation of power output vs. vehicle weight was linearized from the Virginia Tech demonstration (calculation shown in Figure 9). Shorter wheelbases lead to higher capacity

[9] Davis, Stacy; Diegel, Susan; Boundy, Robert. "Transportation Energy Data Book" Ed. 31. July 2012, Oak Ridge National Labs ORNL-6987.

[10] It is not known at this time whether power scales linearly with weight but it can be approximated for this report.

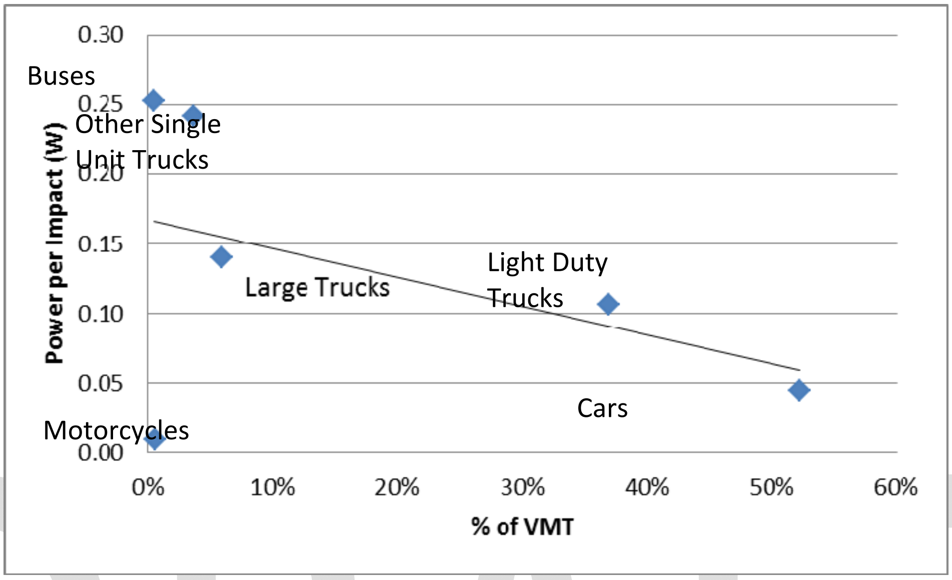
factors, but larger wheelbases tend to be attributed to heavier vehicles. Because heavy vehicles tend to require more axles to distribute weight, wheelbase does not grow linearly as vehicle weight grows, but tends to level out for heavier vehicles. For example, a tractor trailer that measures 68 feet long with five axles has an average distance between axles of 13.6 feet and it will be carrying loads >33,000 pounds. A bus can have similar load requirements but may have a shorter wheelbase of 15-19 feet with only two axles. Because lighter vehicles have shorter wheelbases, they tend to have higher capacity factors, yet lighter vehicles generate less power. The vehicle type versus the estimated capacity factor at 40 and 65 mph, respectively, is shown in Figure 11. Comparison of Figure 10 to Figure 11 shows the engineering compromise in roadway energy harvesting; heavy vehicles generate the most power, but they are less frequent, while smaller vehicles have the highest capacity factor, yet they generate the least power.

Figure 9: Estimation of Power Output as a Function of Weight on the Vehicle Wheel (Virginia Tech Basis)



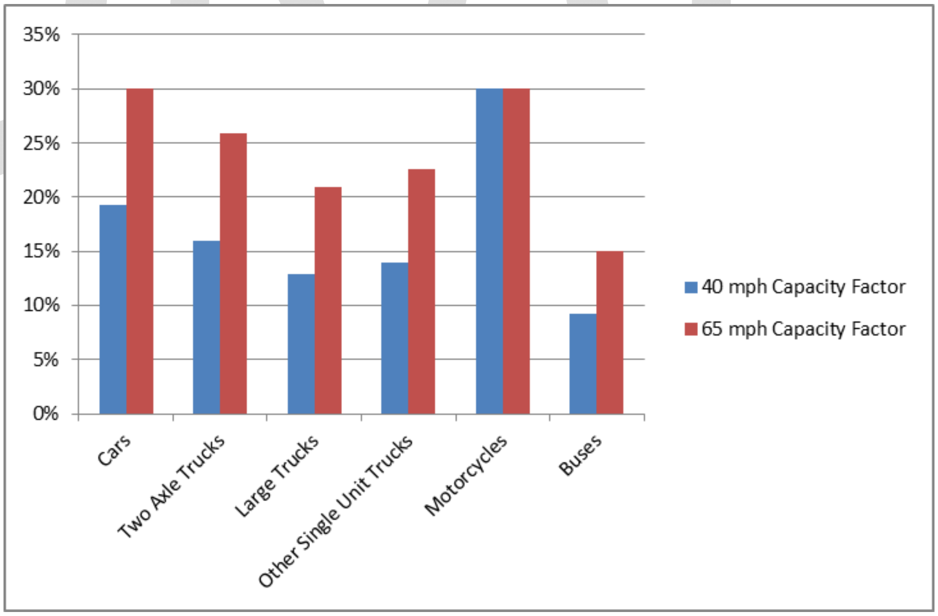
Source: DNV KEMA

Figure 10: The Majority of VMT is Comprised of Passenger Cars and Light Duty (Non-commercial) Trucks



Source: DNV KEMA

Figure 11: Vehicles with Shorter Wheelbases are also Lighter, but they have Higher Estimated Capacity Factors

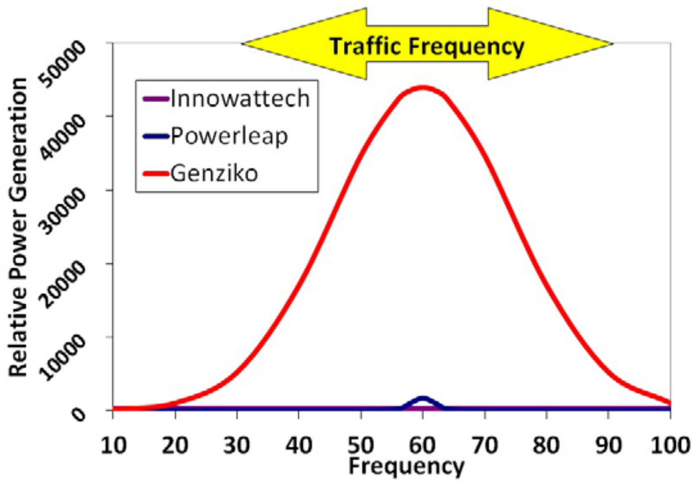


Source: DNV KEMA

Increased Capacity Factor through Longer Power Duration

The previous discussion indicates that capacity factor is dependent on wheelbase and vehicle speed. However, it is also dependent on the length of the power pulse from the energy harvester. A manufacturer (Genziko) claims such advantages (see Appendix A on page **Error! Bookmark not defined.**). The Genziko product literature displays data based on traffic volumes but also makes an effort to quantify a capacity factor based on vibration frequency harvested from the roadway. At 65 mph, tractor trailer impacts would occur at 7 Hz. Therefore, there must be another vibration harvested. The Genziko design harvests vibrational modes using an array of novel micro-scale piezoelectric harvesters in order to extend the power pulse. The extent of this power pulse is critical to whether the system can generate profitable energy.

Figure 12: Genziko Claims Significant Power Density over Competing Technologies



Source: Genziko

CHAPTER 2: Cost Analysis of a Piezoelectric Roadway Energy Harvesting System

Both roadway and railway systems are considered in this report but there are more reference materials available for a roadway system. Therefore, it is not possible to provide as much information about the cost of energy for a railway system, although it would appear that the capital and installation costs of railway systems are less than the costs for roadway systems. The following sections estimate the cost of roadway energy harvesting systems using the evaluations of vendor claims as well as simplified traffic models.

An analysis of the cost metrics indicates that a roadway or railway model would comprise a number of key factors for consideration:

- Maximum power output of module (its rated power density)
- Duration of power pulse from module
- Lifetime of the system and its components
- Traffic volume
- Traffic wheelbase
- Weight of vehicles
- Average speed of traffic
- Capital costs of technology and installation
- Maintenance and other operational costs

Vendor Claims and Demo Data

In Table 2, two different vendor technologies are compared. It can be seen that from the same traffic flow rate, very different power levels are claimed. The table shows that the Genziko product claims 90 times more power with the same traffic flow rate, 50 percent higher vehicle speeds, and 80 percent less modules. Disparities are observed in the categories of traffic speed, power output, the number of units, and the cost per km. The following analyses will separate out the factors that lead to these differences and identify the key metrics that differentiate one technology from another. While the capital cost is high, the LCOE has an opportunity to be low because of increased energy density. This will be examined in the following sections.

Table 2: Two Different Energy Harvesting Technologies Compared for a 600 Vehicle/hr Flow Rate

	Innowattech Numbers	Genziko Numbers	Difference - Genziko vs. Innowattech
Vehicles per hour	600	600	0.0
Vehicle speed (mph)	45	65	0.5
Claimed power generated, 1 km (kW)	150	13,600	89.7
Number of harvesters, 1 km	9,800	2,037	-0.8

	Innowattech Numbers	Genziko Numbers	Difference - Genziko vs. Innowattech
Cost per km	$650,250	$27,200,000	40.8

A summary of the known literature for piezoelectrics is shown in Table 3. Much of the data is presented in different sources and therefore different units. A consolidation of the data into comparative units is summarized in Table 3.

Table 3: Data Summary for Piezoelectric Materials and Installations

Parameter	Low Estimate	High Estimate	Source	Objectivity Ranking (1=low, 3=high)
Optimal vibration frequencies (Hz)	100	120	Cook-Chennault	3
Tested wheel speeds (mph)	7.5	15	Virginia Tech	3
Voltages (V)	400	700	Virginia Tech	3
Amperage (mA)	0.2	0.35	Virginia Tech	3
Power Duration (s)	0.1	0.2	Virginia Tech	3
Maximum measured power per event, (W)	0.08	0.14	Virginia Tech	3
Virginia Tech Traffic Flow speed (mph)	40		Virginia Tech	3
Virginia Tech Traffic Flow rate (vehicles per day)	4,000		Virginia Tech	3
Oregon DOT Traffic Flow Rate (vehicles per hour)	600		Oregon DOT	3
Energy Generated for 1.0 km, Oregon (kWh/month)	350,000		Oregon DOT	3
Number of harvesters, Oregon DOT	6,000		Oregon DOT	3
Energy harvested for bridge mounted devices, per vibration (microJ)	18		S.F. Ali, et al	3
Vehicle speed for micro harvesters (m/s)	25		S.F. Ali, et al	3
kW per km	0.0018		Berkeley	3
units per km		10,000	Berkeley	3
Axles per vehicle	2	8	Berkeley, Oregon	3

Source: DNV KEMA Energy and Sustainability

Table 4: Data Sources from Less Objective References

Parameter	Low Estimate	High Estimate	Source	Objectivity Ranking (1=low, 3=high)
Target Cost of piezoelectric material (per unit)	$1		Channel Technologies	2
Energy generated in 1 km stretch of road (kWh)	400	600	POWERleap, Treevolt	1
Time span of energy measurement (hr)	16		POWERleap, Treevolt	1
Traffic flow rate, POWERleap (vehicles/hr)	12.5	25	POWERleap, Treevolt	1
Vehicles per hour	600		POWERleap	1
Power rating (kW)	720		POWERleap	1
Length of energy harvesting section (km)	1		POWERleap	1
Number of harvesters per 1 km	6,000		POWERleap	1
Power per unit per impact (W)	10		POWERleap	1
Power generated per sq ft, foot traffic (W/ft^2)	1.13		Piezo Power	1
Cost per square foot, foot traffic ($/ft^2)	$1.50		Piezo Power	1
Power rating, 1.0 km (kW)	200		Innowattech	1
Power rating, train (kW)	120		Innowattech	1
Traffic flow rate (vehicles per hour)	600		Innowattech	1
Vehicle speed (kph)	72		Innowattech	1
Train speed (wagons/hr)	300		Innowattech	1
Size of each unit (ft^2)	1		Virginia Tech	3
Power per km (kW)	100		Innowattech, Haaretz article	1
Cost per km ($)	$215,400	$650,000	Innowattech, Haaretz article	1
LCOE ($/kWh)	0.06	0.08	Genziko	1
Lifetime (y)	20		Genziko	1
Installation cost ($/W)	0.4		Genziko	1
Capacity Factor	0.32	0.4	Genziko	1
Vehicles per hour	600		Genziko	1
Power Density (kW/km)	13,600		Genziko	1

Parameter	Low Estimate	High Estimate	Source	Objectivity Ranking (1=low, 3=high)
Long dimension of unit (m)	0.45		Genziko	1
Short dimension of unit (m)	0.3		Genziko	1
Genziko Units per km	2,222	3,333	Calculated from Genziko	1
Number of harvesters	9,800		Calculated from Virginia Tech and Berkeley	1

Source: DNV KEMA Energy and Sustainability

Relationship between Traffic Parameters and Harvester Characteristics

The importance of traffic data such as vehicle weight and wheelbase was shown in "Effect of Wheelbase on Capacity Factor" on page 14. Some additional considerations of that data shown in Figure 13 is the factors that contribute to net power output are vehicle weight, vehicle spacing, power pulse width, and wheelbase. In order to prioritize the importance of these factors, they can be analyzed with a range of values for each parameter in a calculation to model net power output or economic performance. Then, regression analysis can be performed to understand the effect of each parameter on the calculation.

Regression analysis is a way of observing how dependent variables change when independent variables are varied. For example, it is useful to see how the LCOE of the system (a dependent variable) changes when the lifetime of the system is varied (an independent variable). The regression coefficient is a measure of the relative influence each variable has on the LCOE. A negative regression coefficient corresponds to a negative influence on the LCOE, and a positive coefficient corresponds to a positive influence on the LCOE. As a result, the regression coefficients indicate the sensitivity of the LCOE to the input parameters and are a risk ranking system. A coefficient value of zero indicates that there is no relationship between the input and the output. A value of + 1 or - 1 indicates a 1 or -1 standard deviation change in the output for a change in the input of 1 standard deviation.

The chart shows that three of the main factors that affect system level power output are traffic dependent. The only factor that can be controlled by the technology (besides its ability to maximize energy harvested) is the duration of its power output.

Table 5: Correlation between Traffic and Harvester Metrics and System Power Output

Regression Coefficient	Affected Power Metric
Vehicle Weight	Maximum energy harvested – power output (W) at harvester

Regression Coefficient	Affected Power Metric
Vehicle Spacing	Capacity Factor
Power Pulse Width	Capacity Factor
Wheelbase	Capacity Factor

The regression coefficients below were computed by using traffic data from the Transportation Energy Data Book to calculate capacity factor based on traffic speed and vehicle wheelbase. In addition, distributions of vehicle weights from the same data and assumptions about vehicle spacing were included. These numbers were used to fairly estimate the vehicle characteristics of a typical United States roadway, and then these numbers were adjusted to match the numbers quoted by manufacturers. For example, at roadway speeds near 65 mph and a vehicle spacing rate of 0.06, the traffic flow rate approaches 600 vehicles per hour and the system capacity factor approaches 20 percent.

Capacity factor is computed by the time between vehicle axle hits divided by the power pulse width. If the time between axle hits is less than the pulse duration, capacity factor is 100 percent. However, there is a need for a scaling factor to account for the fact that vehicles do not travel bumper-to-bumper and some spacing between them is permitted, which is called the *vehicle spacing occupation fraction.*

Uncertainty in the duration of the power output (power pulse) is constructed around the data from Virginia Tech, which indicated a ~0.1 second pulse width. Since manufacturers do not quote their unit output directly, this was estimated and the input parameters were varied in order to approach cost of energy estimations similar to mature advanced energy technologies. By approaching the problem this way, a traffic-inferred estimation can be used to cross-validate vendor claims and reveal the performance requirements in order to achieve claimed cost of energy.

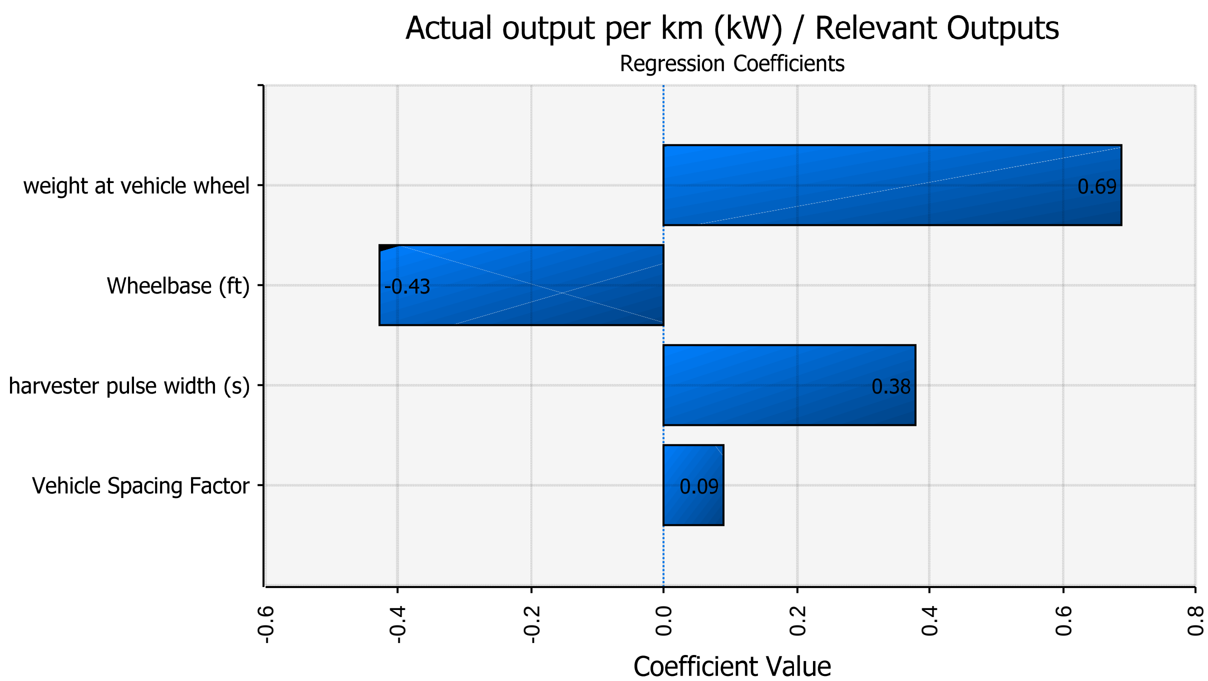
The lessons learned from this analysis are:

1. Power output is increased for heavier vehicles
2. Traffic spacing, wheelbase of vehicles, and output power pulse width dictates capacity factor
3. Power output can be increased in harvester pulse width is increased.

The last point (#3) illustrates the advantage that a technology like Genziko might have in comparison to Innowattech, provided that the output is verified and the vehicle weight influence is similar. If power output is sustained for longer durations with a longer power pulse, capacity factor is increased.

As shown in Figure 13, the system output for 1 km of roadway is largely dependent on the weight of the vehicle and its wheelbase, in addition to the pulse width of the harvester and the vehicle speed.

Figure 13: System Output for 1 km of Roadway



What is the Power Output Required per Harvester?

An analysis of the traffic-based model that generated the regression coefficients in Figure 13 can be used to test the effect of inputs on critical outputs such as capital cost and cost of energy. This analysis reverses the analysis done in "Cost of Electricity of a Compression-based Piezoelectric Roadway Energy Harvesting System –Vendor Claims". In that analysis, vendor claims are used to estimate the cost of energy. In the traffic model, the technology characteristics are interrogated to determine what combinations are needed to create a reasonable cost of energy; it is equivalent to fixing the cost of energy and back-calculating the inputs.

The goal of the following calculation is to determine which metrics an ideal piezoelectric roadway energy harvesting system would have in order to achieve a reasonable cost of energy.

The following information is an extract of useful metrics that permit direct comparison across manufacturers by decoupling performance from traffic-based data. The two tables represent cases for lifetimes of 1-5 years and 10-20 years, respectively. The tables were calculated with the following assumptions:

1. Total installed cost ($650,000-$1,000,000/km per Innowattech assumptions)
2. Harvester size (~8"x8" per Innowattech assumptions)
3. Pulse width (0.1s)
4. Vehicle characteristics for weight per wheel and wheelbase (previous sections)
5. Vehicle flow rate (600 vehicles/hr, 65 mph)

6. Electricity sale prices equivalent to those near Sacramento, California (Figure 19).

Since this model is generalized to show the sum of measured energy output, the capital cost implicitly assumes a total system cost including BOS which may include energy storage and power electronics to output grid-ready energy. In Table 6 the system requirements for a longer lifetime (10-20 years) are shown. A lifetime of 20 years is acceptable for typical road maintenance schedules.

Table 6: Estimation of Key Performance Characteristics of Piezoelectric Systems based on Traffic Parameters with a 10-20 Year Lifetime

Power Output per Harvester (W)	50th Percentile Net Present Value (NPV) at 5 Years	LCOE ($/kWh)	Capital Cost of System ($/kW)	Nameplate Power Density (W/ft^2)	Actual kW/km
79	-$451,000	$0.19	$17,100	179	38
132	-$313,900	$0.11	$10,200	298	64
265	$30,190	$0.06	$5,100	596	128

The lessons learned from the above tables are that an ideal system will have characteristics similar to the following list:

1. Power density >300 W/ft^2 (in this case a module output >150W)
2. A 10-20 year lifetime
3. Capital costs <$10,000/kW
4. Actual kW/km > 100

These parameters can be used as a coarse qualification list to determine the feasibility of technology, and when power density and output is verified by testing, the methods shown in this report can be used for a better estimation of the LCOE.

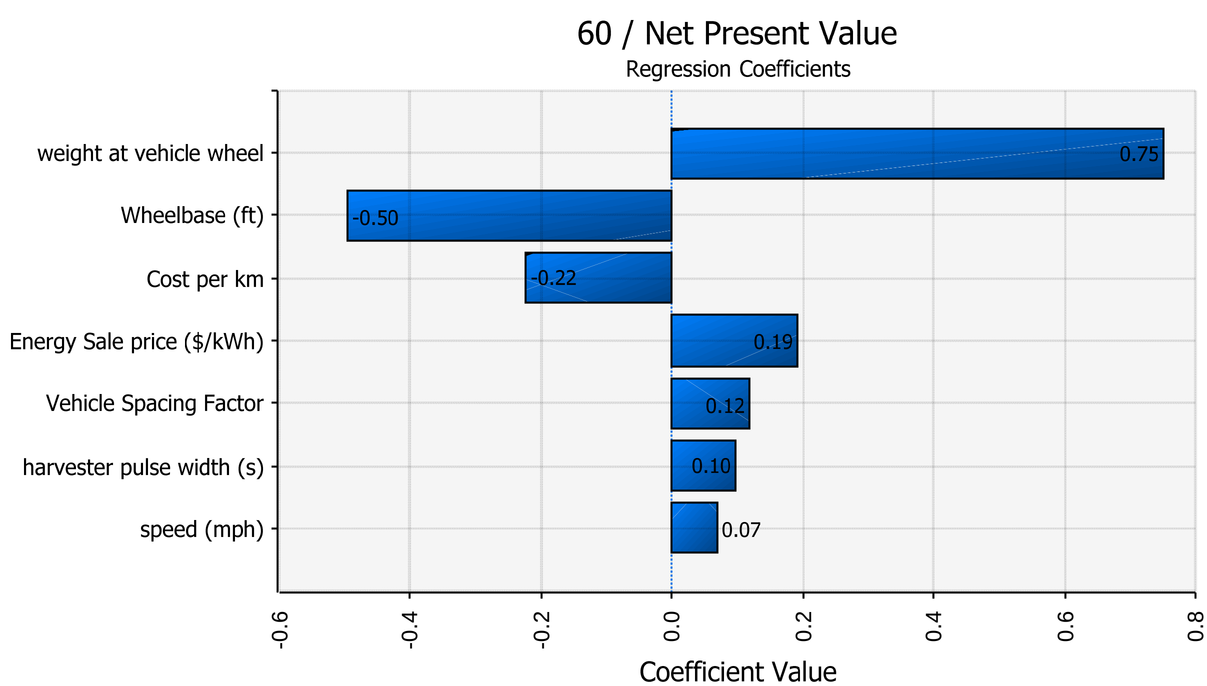
Given these factors, the sensitivity of the five year NPV of the investment is dominated by the weight at the vehicle wheel. When this value is increased, the NPV increases. It is useful to note that a decreasing wheelbase reduces the return because this tends to correlate with lighter weight vehicles even though shorter wheelbases increase capacity factor (for example, small cars and motorcycles). Higher capital costs obviously increase the cost of energy and delay the return in investment. For scenarios with lower power density, the capital cost becomes an increasingly stronger negative influence on NPV. Increasing the harvester pulse width and increasing the vehicle spacing factor (more dense traffic) will increase the payback and the amount earned per kWh sold to the grid. Increasing traffic speed will also increase the return rate (Figure 14). These factors are summarized in Table 7.

Table 7: External Factors such as Traffic and Economics, which Affect System-level Performance

Parameter	Influence on Power System
Weight at vehicle wheel	Power per module, total system power and nameplate rating
Wheelbase	Capacity factor
Cost per km	Capital cost, ROI, NPV, LCOE
Energy sale price	ROI, NPV
Vehicle spacing factor	Capacity factor
Harvester pulse width	Capacity factor, actual system output
Speed (traffic speed)	Capacity factor

The above tables and charts illustrate the important factors that determine the effectiveness of any piezoelectric energy harvesting technology. Since each technology has specific requirements, the deterministic values will vary but should generally follow the trends above and should produce comparable power density metrics.

Figure 14: Regression Coefficients for the NPV (at 60 months) for the Traffic Model LCOE Calculation



Cost of Electricity of a Compression-based Piezoelectric Roadway Energy Harvesting System –Vendor Claims

If the vendor claims are considered independently of the traffic model, then the LCOE can be estimated, but it will not break down information by traits such as traffic characteristics and power pulse duration.

Using vendor supplied information, the cost of electricity depends strongly on the lifetime of the system and the associated maintenance costs to prolong its life. Therefore this analysis is based on some assumptions about the lifetime of the system and is divided into three scenarios. In the first, a relatively short lifetime of five years is assumed. In the second, a longer maximum life of 10 years is assumed. In the third, a lifetime of 30 years is assumed. In all cases, the LCOE assumes a discounted value for future costs over time and sums those costs over 240 months (20 years – corresponding to the expected useful life of road materials) into a net present value. It also sums the energy generated over that time and divides the discounted investment total by the total energy generated to determine the LCOE. Details of the LCOE calculation are provided in Appendix E: Calculation Details.

Factors that have not been accounted for in this analysis are downtime associated with maintenance, reliability of the energy generated or failure rates of the piezoelectric devices, individually sorted costs for inverters (assumed to be lumped into the quote of the installed capital cost) and any additional maintenance required for the roadway during system operation. A summary of the cost results is given in Table 8.

It should be noted that this cost analysis addresses roadway energy harvesting specifically using vendor claims, which have been shown to be much higher than what is actually demonstrated. Lack of data about the installation and capital costs for railway systems presents significant uncertainty into an estimate of a railway system cost.

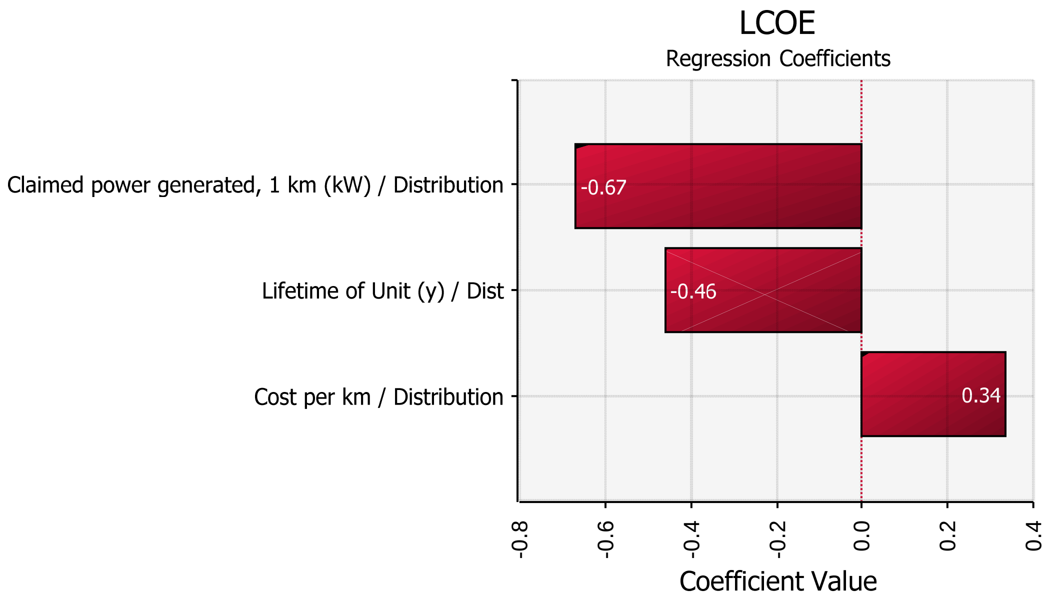
Table 8: Summary of the LCOE Analysis for Three Cases

Case	Minimum LCOE (/kWh)	Maximum LCOE (/kWh)	Mean LCOE (/kWh)	Standard Deviation, LCOE (/kWh)
Case 1: Maximum 5 Year Lifetime	\$0.027	\$1.15	\$0.18	\$0.14
Case 2: Maximum 10 Year Lifetime	\$0.014	\$0.41	\$0.08	\$0.05
Case 3: Maximum 30 Year Lifetime	\$0.004	\$0.20	\$0.03	\$0.02

Source: DNV KEMA Energy and Sustainability

A sensitivity analysis of the LCOE factors is shown in Figure 15. The figure is the sensitivity plot for Case 1, but it shows the same trend in all cases. The sensitivity analysis reflects regression coefficients.

Figure 15: Sensitive Factors Affecting the LCOE



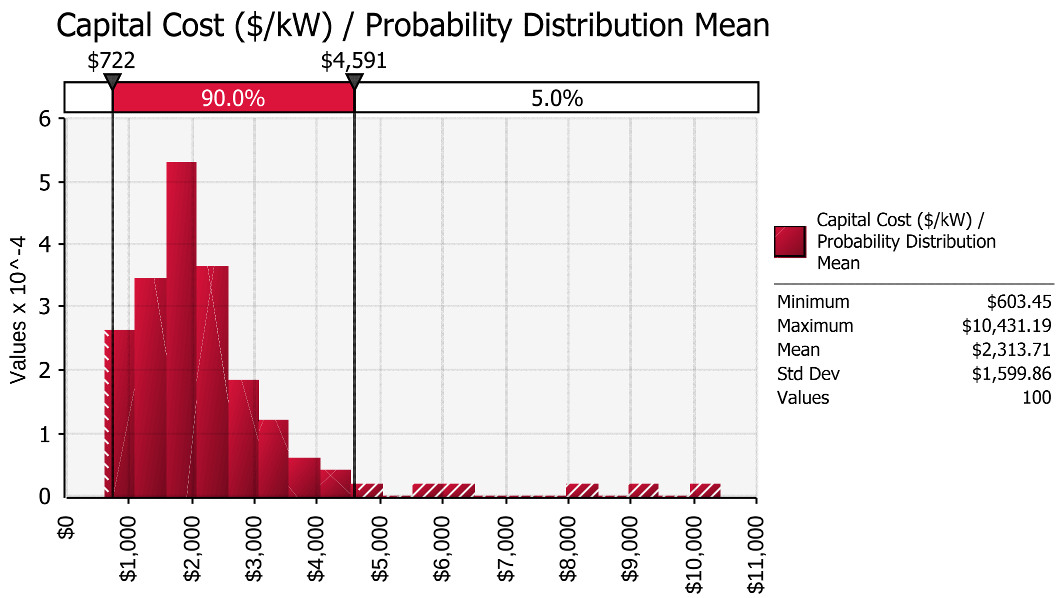
Source: DNV KEMA Energy and Sustainability

The regression analysis indicates that in all cases, the largest uncertainty factor is the claimed power generated, which is directly dependent on traffic factors and the reliable output of the system. This factor is negatively correlated with the LCOE, meaning that if the power generated is higher, the LCOE is driven lower. The second largest uncertainty factor is the lifetime. It is also negatively correlated and it indicates that if the lifetime is longer, the LCOE is driven lower.

There are degradation factors that will decrease power output over time. Since the sensitivity analysis indicates that power output is the most important factor, followed by lifetime, it can be seen that the two factors are coupled and are paramount to the successful performance of the system.

The capital cost ($/kW) is built from the literature sources and is shown in Figure 16 and is calculated from the range of power values and installed costs extracted from the data summary for a 1 km installation (recall Table 17). The mean value of the capital cost is $2,300/kW with a maximum near $10,400/kW and a minimum of $600/kW, and a standard deviation of $1,600/kW.

Figure 16: The Capital Cost of the System Based on Stated Power Capability and Capital Costs from the Literature Review



Source: DNV KEMA Energy and Sustainability

Due to uncertainty concerning the capital and installation costs for railway piezoelectric energy harvesting devices, it is not yet possible to provide a useful LCOE prediction. However, it may be possible to assume that the LCOE is similar to or less than what has been estimated in this report due to the assumption that the capital and installation costs are less. It may also be possible to assume that the regression coefficients would be similar, for example, the return on investment (ROI) would be similarly dependent on traffic volume, lifetime of the system, and cost per kilometer or mile.

Comparison with Traffic Model

Using the traffic model, the following compression-based harvester inputs are used:

- Harvester spacing: 8″
- Harvester pulse width: 0.1s
- Lifetime: 10-20 years
- Length of installation: 1 km
- Cost of Installation: $650,000
- Traffic speed: 45 mph
- Vehicles per hour: 600

Using traffic metrics such as those shown in Figure 41 and the Transportation Energy Data Book's explanation in the section titled *Energy Density of Compression-based System* (described on page 11 of this report), traffic models were tested in two cases to establish if the outputs match the Innowattech claims. First, the parameters were tuned to achieve the cost of energy that was determined in *Cost of Electricity of a Compression-based Piezoelectric Roadway Energy Harvesting System –Vendor Claims* and compared to what is known about Innowattech's claims. Second, the parameters were tuned to achieve the power rating that Innowattech claimed and then checked for agreement. The results of this comparison are found in Table 9. Note that both systems have power densities near or above 300 W/ft².

Table 9: Cross Check of Traffic Model against what was Determined from Innowattech Numbers

Fixed Parameter	LCOE = $0.11/kWh	kW/km = 100-200	
	Traffic Model	Traffic Model	Innowattech
Power per unit (W)	132	265	Not given
Capacity factor	0.05	0.05	Not given
Capital cost	$10,200/kW	$5,100/kW	Mean $2,300/kW, see Figure 16 – max is $10,400/kW
Nameplate Power Density (W/ft^2)	298	596	Not given
Actual capacity factor adjusted output (kW/km)	64	128	100-200
Nameplate system power (kW/km)	1,303	2,607	Not given
LCOE ($/kWh)	$0.11/kWh	$0.06/kWh	Calculated in previous section

Table 9 illustrates that if the cost of energy is to be achieved, it is difficult to meet the capital costs quoted by Innowattech or the power output (kW/km) while holding all of the other requirements. Alternatively, in order to obtain the power ratings quoted by Innowattech, the capital costs appear to be higher than desired and the LCOE becomes lower than what was calculated. The implication is that the quotes from the vendors may be from mutually exclusive conditions, or the conditions are different that what would be expected with United States traffic.

Refinements to the traffic model may be needed to close the gap between these disparities. The purpose of Table 9 is to discover the inherent compromises in technical systems, where achieving a low LCOE is difficult to do when increasing power density accompanies increased capital costs, as an example. The traffic model may be illustrating that vendor-quoted metrics may be the best results for mutually exclusive scenarios. It is beneficial to explore these possibilities and identify objective metrics, such as power per module, to test in a third party manner in order to remove the contingencies and qualifiers associated with metrics such as kW/km.

Cost of Electricity from Vibration-based Roadway Energy Harvesting System – Based on Vendor Claims

The Genziko product has substantially different claims than the compression-based (Innowattech) device. For a 600 vehicle per hour traffic flow rate, the Genziko sales presentation claims $2/W ($2,000/kW) installed cost *including* 1 MWh of storage per MW of installed power, with performance of 13.6 MW/km. The Genziko literature differs from POWERleap and Innowattech discussions in that it specifically mentions energy storage. There is only one source for the Genziko data; therefore, there are not enough cross-referenced values to place bounds on the uncertainty, and the result is that the LCOE calculation is somewhat deterministic. This is why the values in Table 10 have very little variation as the estimated lifetime increases.

Table 10: LCOE for the Genziko Technology Based on Vendor Information

Case	Minimum LCOE (/kWh)	Maximum LCOE (/kWh)	Mean LCOE (/kWh)	Standard Deviation, LCOE (/kWh)
Case 1: Maximum 5 Year Lifetime	0.05	0.22	0.10	0.03
Case 2: Maximum 10 Year Lifetime	0.03	0.04	0.03	0.004
Case 3: Maximum 30 Year Lifetime	0.01	0.01	0.01	0

Comparison with Traffic Model

The Genziko unit has dimensions of 0.3m x 0.45m x 0.25 cm. The unit footprint is ~11.8x17.7" (average 15"). In order to obtain the cost of energy that the manufacturer claims ($0.06-0.08/kWh), it is estimated that for 65 mph traffic with United States-based vehicle populations, the following is assumed:

- Harvester spacing: 24"
- Harvester pulse width: varied between 0.2-1.0s
- Lifetime: 10-20 years
- Length of installation: 1 km
- Cost of Installation: $27,200,000
- Traffic speed: 65 mph
- Vehicles per hour: 600

The result of this calculation is that there is an assumed 3,280 units per km. Since the Genziko marketing presentations contain a lot of information with different claims, the best attempt at identifying a set of self consistent claims was attempted in the last column of Table 11. In this table, four factors are tested with the traffic model in order to find agreement with the Genziko claims: (1) LCOE, (2) claimed power generated (kW/km), (3) capacity factor, and (4) capital cost ($/kW). The results are shown in Table 11, and the conclusion is that, based on the information provided, it appears that some parameters are mutually exclusive until further clarification is provided. For example, it appears difficult to achieve $0.06-$0.08/kWh and the high power output of 13.6MW/km claimed when holding the constraints on United States traffic characteristics. In order to achieve high power outputs per km, the power density of the units must be very large, in the 12-13 kW range. However, at these power output levels the LCOE becomes very low (lower than what Genziko claims). The main point is the table shows that with the characteristics of United States traffic and with what is inferred about the power output of the units, these high power outputs with an LCOE of $0.06/kWh appears to be mutually exclusive. Either the power output is less or the cost of energy is more.

An attempt to match the majority of the Genziko claims was made by matching the nameplate power capacity to the stated power capacity. If the capacity factor adjust power is set near 13.6 MW/km, it is found that the capital costs approach $2,000/kW, and the LCOE approaches $0.02/kWh. In this case, the capital cost, actual power output and capacity factor match the claims, but the LCOE is much lower than what Genziko claims. This is only possible with very high module power ratings near 13 kW.

Table 11: Cross Check of Traffic Model against what was Determined from Innowattech Numbers

Fixed Parameter	LCOE = $0.06-0.08/kWh	kW/km = 13,600	Capacity Factor = 42%	Capital Cost = $2,000/kW	
Reference	**Traffic Model**	**Traffic Model**	**Traffic Model**	**Traffic Model**	**Genziko**
Power per unit (W)	3,973	12,714	2,649	13,243	Not given
Capacity factor	0.32	0.32	41%[11]	0.32	32-42%
Capital cost	$6,521	$2,038	$7,744	$2,065/kW	$2,000/kW
Nameplate Power Density (W/ft^2)	993	3,178	662	3,311	Not given
Actual capacity factor adjusted output (kW/km)	4,201	13,444	3,538	13,267	13.6 MW/km
Nameplate system power (kW/km)	13,035	41,712	8,690	43,450	Not given
LCOE ($/kWh)	$0.07/kWh	$0.02/kWh	$0.09/kWh	$0.02/kWh	$0.06-$0.08/kWh

[11] Note – power pulse duration increased to 0.5-1.2 seconds, mean 0.8 seconds. This was modified in order to keep the traffic flow rate the same at 611 vehicles/hr.

DNV KEMA Estimates Based on Restricted Assumptions

The Innowattech evaluation determined the LCOE to be $0.11/kWh with an averaged capital cost ranging from $2,300-$10,400 per kW (mean $4,000/kW). With the traffic model, two scenarios can be run to test the mutual exclusivity of the LCOE and capital cost. Using the parameters described in Table 12, parameters were tuned to either achieve an LCOE of $0.11/kWh or a capital cost of $4,000/kW, and the resulting values were achieved. The capital cost for a target LCOE of $0.11/kWh is near $10,000/kW, and the LCOE for a target capital cost of $4,000/kW is below $0.06/kWh (shown in Table 12). To be consistent, the parameters that were often quoted in the product literature such as vehicle flow rate (600 vehicles per hour) and vehicle speed (near 65 mph) were maintained. Other assumptions such as harvester spacing were kept consistent with the Berkeley evaluation. The traffic data such as vehicle weight distribution and vehicle wheelbase distribution were taken from the Transportation Energy Data Book. Estimations of power pulse length were based on the Virginia Tech demo and lengthened (see Table 12) by assumption that commercial units have mechanisms to do so. Note that in either case, the power density is above 300W/ft^2.

Table 12: A Test of Mutually Exclusive LCOE and Capital Costs

	Fixed: $0.11/kWh	Fixed: $4,000/kW
LCOE	$0.11/kWh	$0.04/kWh
Capital Cost ($/kW)	$9,615/kW	$4,172/kW
Capacity Factor	0.09	0.13
Vehicle Flow Rate (vehicles/hr)	611	611
Vehicle Weight Distribution (N/wheel)	26,486	26,486
Power Per Unit (W)	143	185
Unit Spacing (in)	8	8
Nameplate Power Density (W/ft^2)	322	417
Nameplate Power System Rating (kW/km)	1,408	1,825
Actual System Output (kW/km)	107	149
Units per km	9,843	9,843
Power Pulse Length (s)	0.1-0.2	0.1-0.5
Average vehicle wheelbase (ft)	11.24	11.24
Vehicle Speed (mph)	60-70	60-70
Cost per km ($/km)	$600,000 - $1,500,000	$600,000 - $1,500,000

Comparison of the Projected LCOE to Distributed Renewable Energy Generation Sources

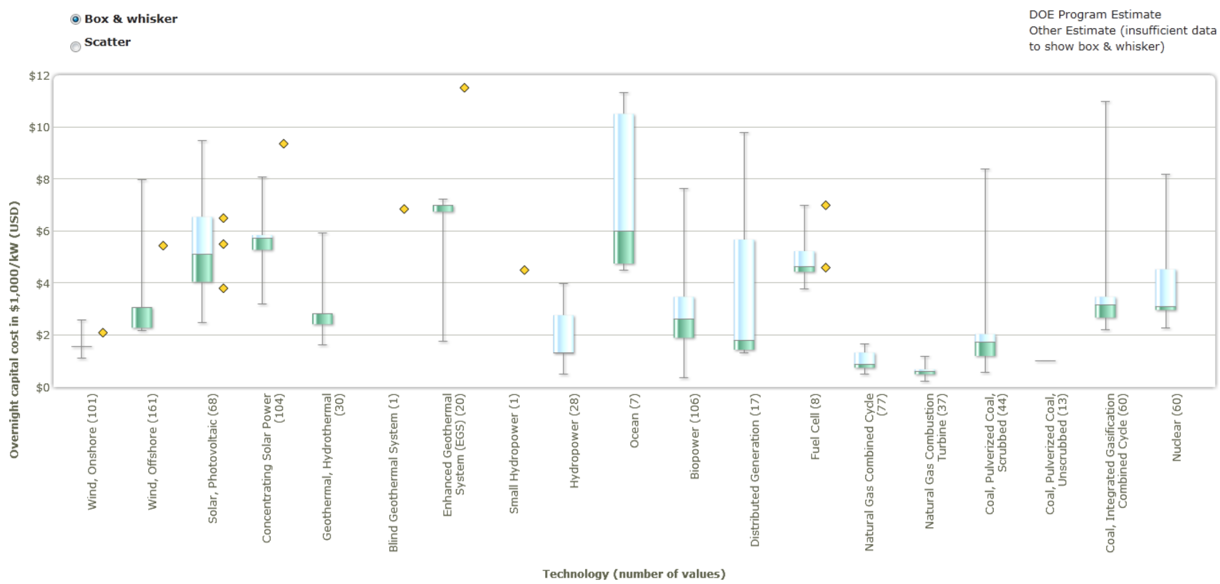
From the above analysis, it has been estimated that the LCOE for compression-based road applications ranges from $0.03-$0.18/kWh. The mean of this range is $0.11/kWh. The LCOE for vibration-based road applications is claimed to be \$0.06-\$0.08/kWh. Using the estimates from Table 12, the DNV KEMA estimates for the LCOE (at \$4,000/kW) and capital cost (at LCOE \$0.11/kWh) are included to place bounds on the estimates. DNV KEMA estimates the LCOE costs to range from \$0.08-\$0.33/kWh.

It can be seen in Figure 17 that extensive analysis has been performed by National Renewable Energy Laboratory (NREL) to compare the costs of various energy sources[12]. The OpenEI database is an open data platform developed by NREL — with the Department of Energy (DOE) support — that catalyzes the world's energy information and provides linked open data about the cost of energy for multiple technologies and regions. Energy information and data are available to use, edit, add, download, and build into analyses, tools, and decisions.

The overnight capital cost is shown in Figure 17. As has been shown elsewhere, the conventional technologies such as coal and natural gas-based power generation consistently enjoy capital costs less than \$2,000/kW. Renewable technologies that come closest to competing with these lower capital costs are onshore wind, hydropower, and – to a lesser extent – biomass and geothermal technologies. It is worth remarking that distributed generation is a consolidated category with overnight capital costs that can approach \$1,500/kW, coming close the cost of grid-scale conventional power systems. This category includes combined heat and power (CHP), distributed wind, residential solar, and other technologies. Similarly, the LCOE for various energy systems is depicted in Figure 18. Note that cost of electricity can range from \$0.05/kWh for conventional technologies to as much as \$0.35/kWh and higher for unconventional technologies. Part of the database that is used to compute the NREL LCOE models was created by Capstone to estimate the cost of energy based on locality. For comparison, estimated energy costs for the Sacramento, California region are shown in Figure 19.

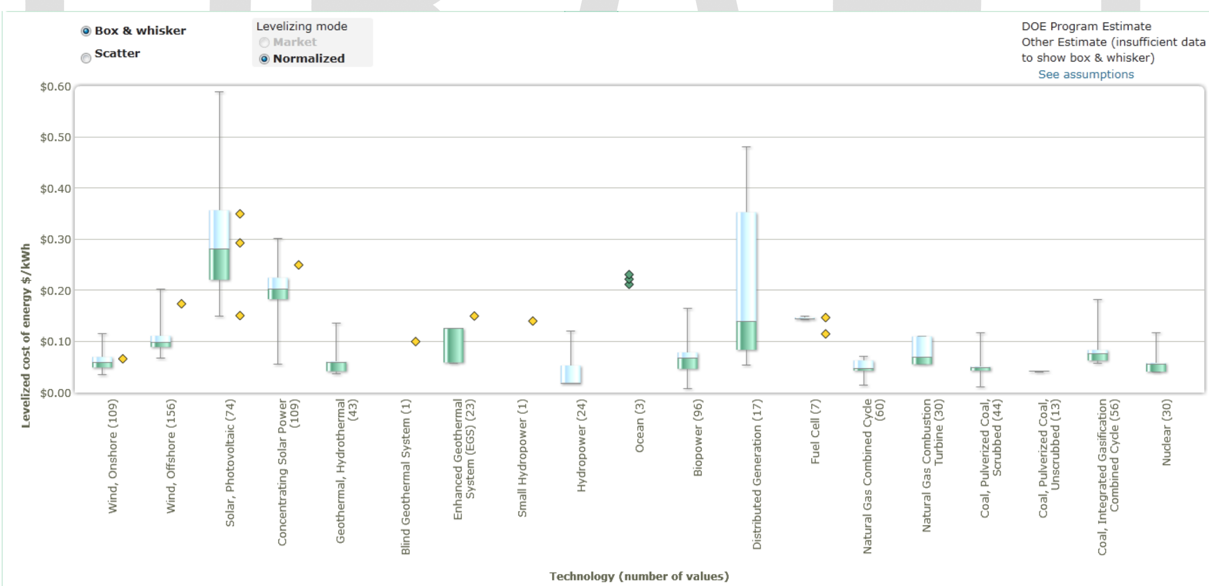
[12] OpenEI: Open Energy Info. http://en.openei.org/wiki/Transparent_Cost_Database. Accessed January 1, 2012. National Renewable Energy Laboratory (NREL), Open Government Initiative, US Department of Energy.

Figure 17: Comparison of Capital Costs for Various Energy Sources



Source: NREL

Figure 18: Estimated LCOE for Various Energy Systems



Source: NREL

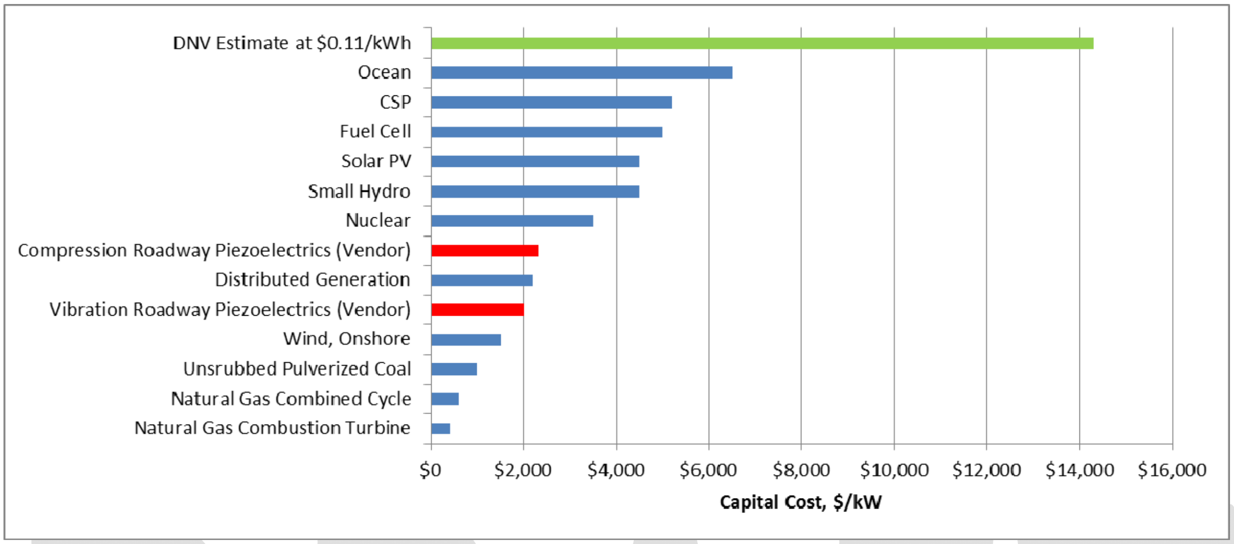
Figure 19: Electricity Costs near Sacramento, California

Source: Capstone, Open EI

This analysis estimates the range of the LCOE for the piezoelectric system to be between $0.08-$0.18/kWh. The charts in Figure 20 and Figure 21 indicate that the compression-based piezoelectric system may have an LCOE less than that of small hydro and fuel cells and capital costs similar to those for distributed generation systems. By vendor estimates, the capital cost appears to be less than solar PV and fuel cells. The DNV KEMA estimate for the LCOE has significant variation but coincides with costs similar to concentrated solar power, distributed generation, and ocean technologies. Compared to the NREL definition of distributed generation, the piezoelectric system appears to have higher capital costs than the average distributed generation system (comprising mainly combined heat and power systems) and an LCOE with a similar spread. To lend more certainty to these calculations, an independent verification of the module output is required. Only then can one begin to ascertain which conditions produce the most favorable power output and LCOE.

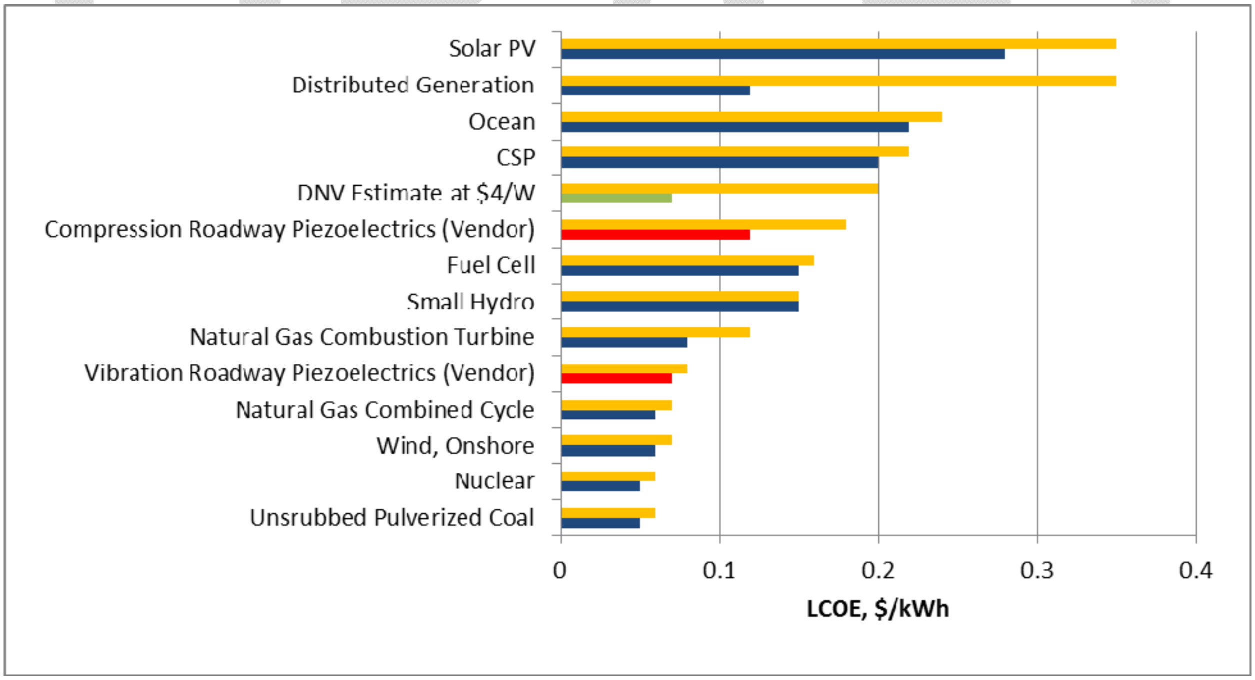
Using the estimates from Table 12, the DNV KEMA estimates for the LCOE (at $4,000/kW) and capital cost (at LCOE $0.11/kWh) are included to place bounds on the estimates. In Figure 20 the mean capital costs are shown. The figure shows that the mutual exclusivity that was found with the LCOE estimates and capital costs is again apparent in this comparison. While minimum capital costs could be as low as $2,100/kW, 90 percent of the values are between $3,700 and $36,000 (Figure 42). In Figure 21 the most likely and 90th percentile values of the LCOE are shown and ranked. The DNV KEMA estimates for the LCOE – on average – are higher than vendor claims, ranging from a mean of $0.07/kWh and 90 percent of the values are less than $0.20/kWh. It can be seen in Figure 43 that 90 percent of the values are less than $0.20/kWh. The sensitivity factors for this estimate are weight at the vehicle wheel and harvester pulse width (Figure 44) and the sensitivity rankings are identical for the capital cost estimate. Since these parameters are not explicitly advertised in product literature, significant uncertainty is placed on these estimates but they can be indirectly derived from United States traffic data. In Figure 20, only the most likely or median values are shown, since the maximum value of the DNV KEMA estimate is close to $90,000/kW due to significant uncertainty in the power output characteristics of the technology.

Figure 20: Capital Costs for Energy Systems Compared to the Piezoelectric System



Source: DNV KEMA Energy & Sustainability

Figure 21: Comparison of the LCOE for the Piezoelectric System Compared to Other Energy Systems



Source: DNV KEMA Energy & Sustainability

Added Value: Data and Reduced Inspection Costs

While the energy harvesting devices may generate energy, there is also the potential to generate vast amounts of data. The value of this data may be difficult to quantify, but it could be explored for the following applications:

1. Real time monitoring of traffic flow patterns that can be used in traffic studies and evaluation of the need for construction or roadway updates.
2. Data to feed into traffic alerts and congestion reports during rush hour.
3. Data to monitor the integrity and health of the roadway to inform maintenance schedules and perhaps save inspection costs.
4. Specific data about vehicle weight which may be incorporated into traffic weigh stations.

As is the case most often with monitoring systems, the opportunity is that the system provides data that may mitigate the need for inspection costs. DNV KEMA performed a cost assessment of Structural Health Monitoring (SHM) monitoring systems for wind turbine blades in 2011, and found the largest component of the savings was in reduced inspection costs[13]. There may be a similar opportunity for using piezoelectrics in roadways.

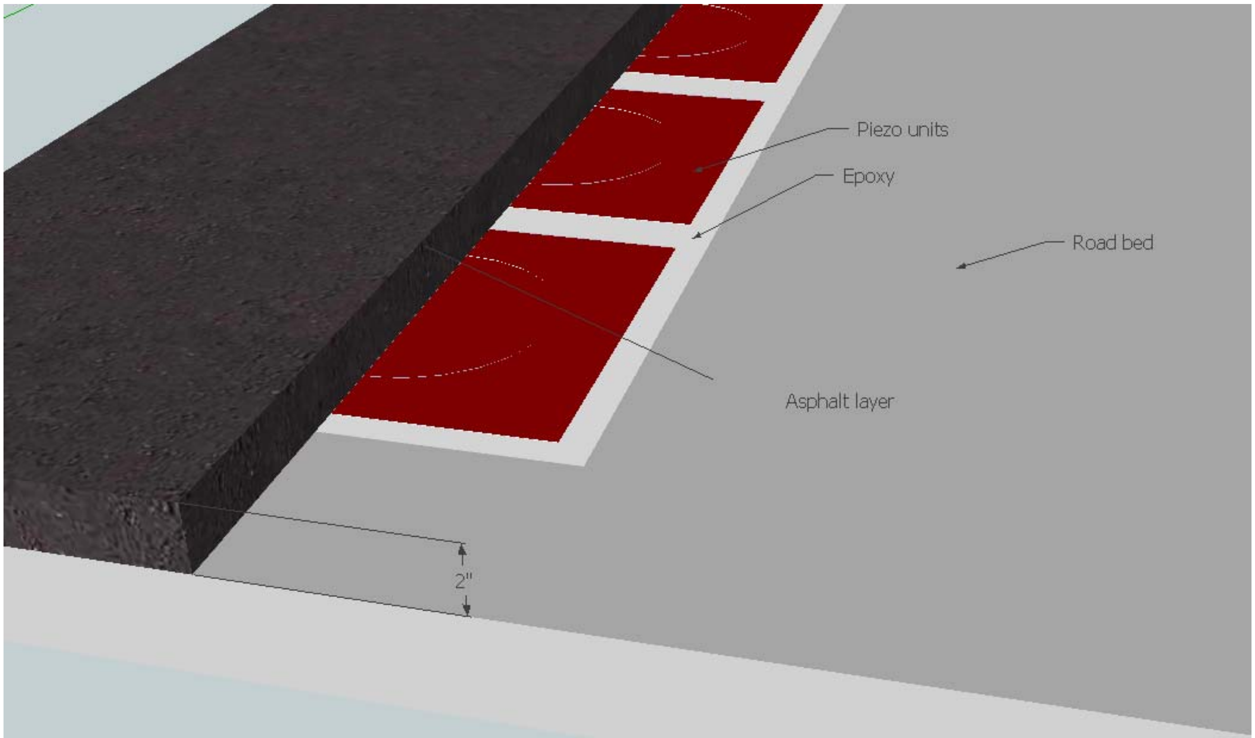
Roadways versus Railways

The roadway installation requires more labor and material to install than a railway application . The units are installed in the road bed and epoxy is used as a filler to permanently affix the units in place, such as what was demonstrated by Virginia Tech. Approximately 2" (5 cm) of asphalt is overlaid. Saw cut channels to run electric connections are required to route wiring to the roadside, and these must also be buried. Because the asphalt layer and road bed are not perfectly rigid, some energy is absorbed by the surrounding layers of material and therefore a larger unit with force-multiplying components is required to harvest significant energy. This affects the cost of installation and operation because greater capital, time, and labor is needed to install the units, and the units are made with greater material volumes to make them robust for the harsh conditions in the roadway. As a result, greater labor costs are required for installation, and greater difficulties are encountered with maintenance. Also in this configuration, a less efficient transformer is used which may lead to 30 percent losses (70 percent pass through efficiency) in conversion of the power signal to usable power.[14] A study funded by the German Federal Highway Research Institute examines these properties in detail.

[13] Hill, D. "Return on Investment for Structural Health Monitoring Systems in Wind Turbine Blades." DNV Report No. 2010-9509, December, 2010.

[14] Milgrom, Charles. Innowattech. Phone conversation, 1/24/2012.

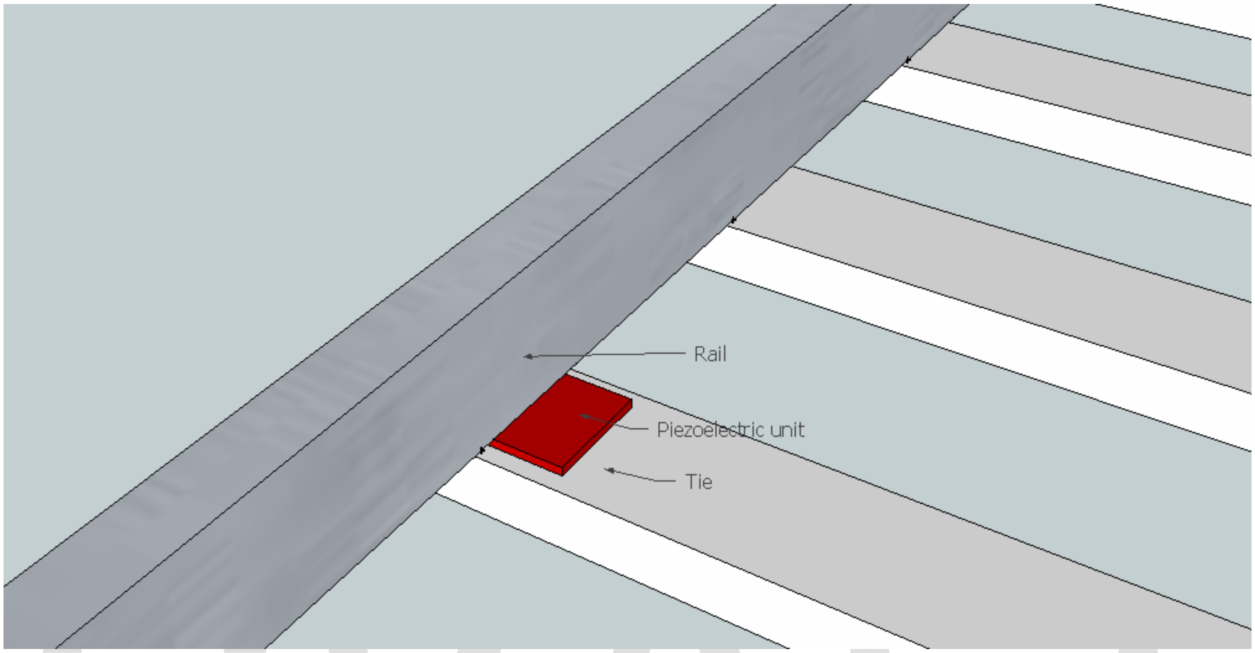
Figure 22: Cross Sectional Diagram of the Roadway Installation of Piezoelectric Energy Harvesters



Source: DNV KEMA

The railway application implies the use of a thinner unit for two reasons: (1) the geometry of the installation requires a thin unit, and (2) there are less inelastic forces in action in this application and fewer discs are needed per unit to harvest useful energy. There are a number of cost-saving opportunities in this installation. The unit is thinner, so it requires fewer piezoelectric discs, thus lowering its capital costs. The unit can be installed between the rail tie and the steel rail and does not require excavation, which lowers the labor required for installation (and lowers installation cost) as shown in Figure 24. Also, because the rail is rigid, it is less elastic than a roadway and therefore imparts more force per unit area on the piezoelectric unit, which improves efficiency. For that reason, these units have higher energy density. The passing rail cars impart more direct energy to the units and consequently there is less dependence on speed. Because the rail cars are on rails, there is 100 percent certainty that a passing car will contact the piezoelectric device and as a result, the efficiency (energy/compression event) is greater than a roadway. Lastly, because the rail system is usually privately owned and there is direct access to nearby power, permitting procedures are less intensive, and connection to nearby power sources is more accessible. The units are easily accessible for maintenance. According to Innowattech, converting the signal to a useable power signal is >90 percent efficient because a more efficient transformer design is possible in this configuration.

Figure 23: Illustration of the Above-ground Installation of Piezoelectric Energy Harvesting Devices for Railways



Source: DNV KEMA

CHAPTER 3: Conclusions and Recommendations

As a result of this analysis, a number of conclusions and recommendations can be made.

- This analysis uses vendor data to estimate the range of the LCOE for the piezoelectric system to be between $0.08-$0.18/kWh. This value is strongly dependent on traffic conditions and vehicle characteristics. Using best estimations from vehicle data, the DNV KEMA estimate is that the maximum for the LCOE is closer to $0.20/kWh.
- A traffic model used approximations to derive traffic characteristics in order to calculate capacity factor and vehicle weights for United States roadways. This data was then used in conjunction with known data about piezoelectric demonstrations in roadways to assess key parameters such as the LCOE and capital cost. Vendor claims have been found to be mutually exclusive, likely indicating the presentation of best values from mutually exclusive conditions.
- Third party validation of power output per module would greatly reduce uncertainty in these estimates. Until the power output per module is transparently quantified with specific conditions under which it can be replicated, cost of energy estimates will contain inherent uncertainty. At this point in time and with the information available, it would appear that power densities of 300 W/ft^2 or more are needed to approach the economic viability claimed by vendors.
- The lifetime of the system needs to be better quantified via demonstration. Present demonstration is limited to two years. Accelerated tests can evaluate lifetime in a more cost effective manner than an actual demonstration.

Stage-Gate Evaluation

A demonstration and thorough evaluation of the technology should attempt to quantify the power output, durability, and lifetime of the system in addition to its performance as a function of traffic volume. Details of how and why these evaluations should occur are provided in Appendix D: Evaluation Criteria.

It is recommended that any research in the area be staged with Go/No-Go gates such that risk for the project funds is mitigated.

Presently there are four potential products for evaluation:

1) Innowattech Roadway harvester
2) Innowattech Railway harvester
3) POWERleap roadway harvester
4) Genziko roadway harvester

It is recommended that if an evaluation path is desired, each of the products be evaluated against one another in an objective, lab-scale evaluation first. In each phase of research, the minimum investment required to answer fundamental questions about power output and lifetime should be considered. For example, in Phase I, such testing can be performed in a modified stress frame with duplicate units from each manufacturer. In Phase II, the accelerated tests can be performed in a similar lab environment with minimized costs in order to verify that promising technologies are also durable in their expected environment. Only in Phase III would a field test be considered, and even in this case a down-selected product group would be considered and may only be isolated to a single location for verification purposes. The suggested scope is shown in Table 13. Further details about the testing phases are included in Table 14.

Table 13: Staged Gate Approach to Evaluation of Various Piezoelectric Technologies

Phase Description	Expected Result/Outcome	Pass/Fail Criteria
Validation of Power Output per module	Tentatively, a power output of 300 W/ft^2 is calculated and required to make the system viable. If power output is promising or if any vendor claims are verified, proceed to Phase II. Determine top performer, select pathway for implementation (road or rail)	Using calculation approaches in this report, verify that power output matches the needed levels for payback to reach the targeted power densities or power per km metrics. If it does not, it shall not proceed to Phase II.
Accelerated Tests	Identify decay mechanisms and durability issues. Reduced list of products from Phase I will be tested. If durability and failure modes are acceptable, proceed to Phase III.	For products that have made it to Phase II, they shall show a cycle life equivalent to critical lifetime, such as 10-20 years. Should account for weathering and other abuse factors.
Field Demonstration	For durable products that have shown acceptable power output, a field demonstration in an appropriate environment should be chosen.	Actual use data should verify the needed power output and durability requirements.

Phase I: Lab Scale Tests

Loading cycling during these tests may be considered provided that the control variables are complimentary to the field tests. Loading and cycling to verify power output should be done in a controlled fashion. Load should be calculated based on simulated vehicle (or train) loads. Power output should be measured and presented in the form of watts per cycle such that this data can be translated to roadway or railway performance. Effect of substrate layers (asphalt, concrete) should be confirmed either experimentally or with finite element analysis (FEA) models. Stress frame tests and FEA modeling examples are provided in Figure 32.

From the above assessments, desired power output should equate to values that generate favorable LCOE estimates as calculated in this report. Products that do not pass these criteria would not be considered for future phases of work.

Considerations of the other standards mentioned in this document (MIL 1376 and ASTM C627) should also be considered while accounting for unique features at the system level.

Phase II: Accelerated Tests

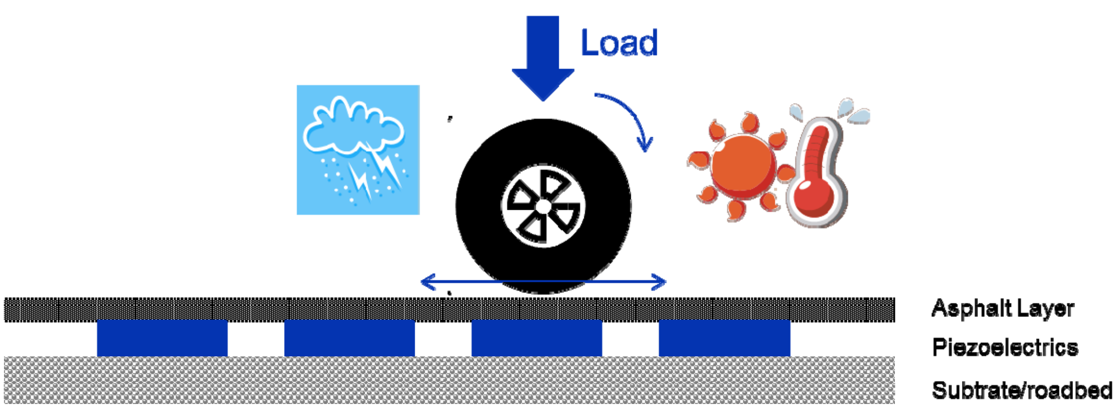
The cost of energy calculation involves an assumed production of energy over the life of the system. Presently, since no data is known about the decay rate of energy production over time, it is assumed to be constant. It is unlikely that this is the case, so this decay rate should be quantified.

To this end, a demonstration should use accelerated testing to identify materials degradation factors. These tests should be designed to identify the dominant decay mechanism, such as moisture, stress, fatigue, or temperature.

The loading of the discs and their exposure to temperature and moisture may be of interest. Examining the power output of the system as compared against common ageing tests such as salt fog (ASTM B117) can be considered. For example, controlled loading conditions over time without weathering or moisture could be compared against the accelerated tests in Phase II to determine if the cycling due to loading is the main degradation factor, or if the added effects of weathering cause the degradation.

Accelerated tests would need to capture the degradation factors that are most harmful to the system life. A suggested schematic of such a degradation system is shown in Figure 24. A device used to simulate a road tire wearing on the surface with variable load can be used to simulate the passing weight and wear of vehicles. Load can be varied to simulate variances in vehicle weight. The repeated action of rolling the wheel across the surface will accelerate the number of cycles on the installation and decrease the time needed to observe degradation indicators. If possible, weathering can be added by introducing heat, cold, rain, or UV to the system to simulate ageing conditions by weather. Power output and system performance should be monitored as a function of control parameters and cycles. A modification to the design in Figure 24 could be made for rail applications, by using a section of rail, a tie, and a loaded wheel on the rail.

Figure 24: Schematic of an Accelerated Ageing Platform for a Piezoelectric Energy Harvester Application

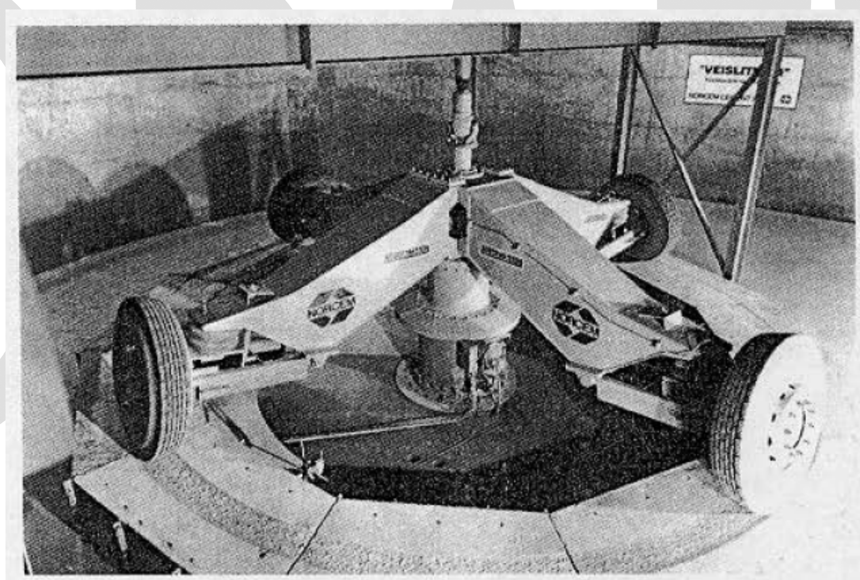


Source: DNV KEMA Energy and Sustainability

The system shown in Figure 25 has been designed in various iterations, as mentioned in a Norwegian test program developed in the Norwegian Masonry and Concrete Research Institute in Norway (see Figure 25).

Careful consideration of the efficient use of time as well as a design of experiments (DOE) based approach to isolate each of the variables and quantify their effect would be required. It should be possible to extract the expected cycle life and test to that parameter in the accelerated tests. For example, if traffic patterns indicate an average of 4,000 vehicles per day, it might be expected that the number of *hits* or *cycles* would be 4,000 vehicles per day multiplied by two tires per vehicle, multiplied by 365 days per year, multiplied by 20 years, or 58 million cycles. In this example, one year represents about two million cycles. Weathering patterns could be controlled according to cycle length to simulate an accelerated seasonal wear pattern for the system.

Figure 25: Efficient Road Testing Jig Designed to Cycle Concrete under Road Wear Conditions



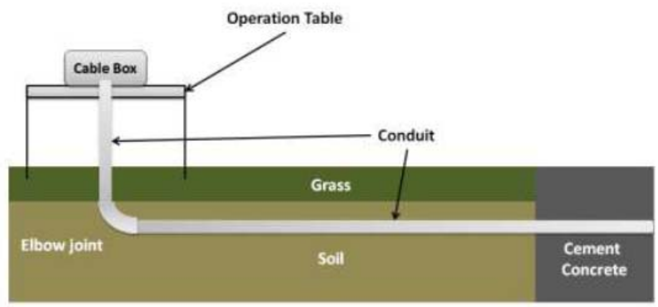
Source: Norwegian Masonry and Concrete Research Institute

Phase III: Field Tests

Field testing can be used to quantify installation costs and information about real-world performance (such as vehicle volume and additional data produced). The combination of accelerated tests and field tests would then place bounds on the lifetime and durability uncertainties identified in this assessment. Assuming products have made it through the first evaluation phases, the field test would be the final confirmation that the product functions as intended and has potential to meet target LCOE and capital cost metrics.

As other demonstrations have shown, a field test should involve actual installation of the system in an actual roadway. The purpose of these tests is to compare actual performance to lab and accelerated test performance and isolate variables associated with real-world application, such as installation of the electronics, associated difficulties with the road surface, and other wear factors. Unlike the prior installations, it should be feasible to examine the performance of the system in asphalt and concrete for comparison. The Virginia Tech field demonstration is shown in Figure 26.

Figure 26: Installation of a Field Demonstration in Virginia Using Innowattech Energy Harvesters (left) and a Schematic of the Installation with Data Collection (right)



Source: Virginia Tech

Suggested Test Structure

Table 14: Outline of Suggested Demonstration Project

Test Phase or Task	Purpose	How the data should be used
Phase I: Lab Tests	Isolate power output as well as controlled tests to verify performance as a function of load or frequency Make first data-validated revision to LCOE calculation.	These tests should determine whether a product passes or fails performance and merits investigation in further Tasks. If LCOE is greater than an unacceptable value (e.g. $0.20/kWh), the product does not proceed to next phase.
Phase II: Accelerated Testing	Quantify ageing factors, energy output decay rate, failure rates. Identify dominant variables associated with decay factors to add confidence to findings from accelerated tests,	Overlay energy output degradation on the cost of energy assessment and determine how the economics are affected. Support and inform the design of the field test and will be used to isolate influencing factors in the accelerated tests. Products that do not show needed durability or cycle life shall not proceed to Phase III.

Test Phase or Task	Purpose	How the data should be used
Phase III: Field Test	Show system performance in real world, isolate real world factors that may influence system performance	Confirm field factors that affect system performance that are not seen in the accelerated or field tests.
Phase IV (continuous throughout project): Revised LCOE and Evaluation	Use degradation factors and energy output data from first 3 tasks to reassess cost of energy.	Refine the calculations presented in this report and give increased confidence to the assumptions used in the assessment of piezoelectric energy harvesting.

Approximate Cost of a Demonstration Project

The Virginia Tech project appears to be a $600,000-$1,000,000 project executed over a two-to-three-year time frame. The project involves some system modification and design as well as installation of the field test.

The demonstration seems to lack critical assessments such as multi-product comparison, lab-controlled power output measurements, accelerated testing, and a finalized cost of energy assessment based on the test findings. A more extensive testing program is needed to add these dimensions. The field test for the Virginia Tech project is not long enough to determine critical ageing factors.

In a staged approach, investment can be minimized by means of short term commitments to each research phase. A laboratory investigation of multiple products could be accomplished for an estimated cost of $50,000-$100,000. If no products pass this stage, the project would be terminated.

If products make it to the second phase, the complexity of accelerated testing would add to the cost but tests could be run for a range of $100,000-$200,000. If no products pass this phase, the project would be terminated.

The field demonstration would likely require an installation site and continued monitoring and processing of data. This would be the most expensive portion of the project and may cost $300,000-$600,000. At each stage, the revised LCOE would be provided based on findings.

The total project cost would range from $450,000 - $900,000, which would cost less than the Virginia Tech demonstration with more value-added data over a ~three year project duration. The value from such a demonstration would determine if piezoelectric materials are a suitable technology to generate clean energy from roadways and improve the overall efficiency of transportation on highways.

Potential Partners and Functions

Potential partners for testing can include UC Davis and Caltrans. Caltrans has the capability of offering field test sites and test beds. Caltrans could be a useful partner in a field demonstration phase.

The laboratory facilities in the DNV KEMA office in Columbus, Ohio are capable of performing lab-scale and accelerated materials tests. If a testing partner in California is desired, DNV KEMA will be able to specify the equipment and expertise needed and work with a subcontracted partner to complete these tests.

In the event of a railway demonstration, Caltrans may still be able to offer testing functions or capability to the common factors between rail and roadway, but there may be a need to identify a willing rail partner for guidance on some tests and/or field application.

UC Davis has both laboratory equipment associated with vehicle testing as well as demonstration capabilities. A facility such as UC Davis may be capable of supporting an accelerated test jig such as the one described in Figure 25 via adaptation of existing equipment or construction of new equipment.

For the purpose of the LCOE evaluation, procedures such as those shown in this report can be used. DNV KEMA is one such partner capable of managing such a project, providing technical leadership toward the test goals, and aggregating the data for the purpose of technology qualification and evaluation.

REFERENCES

Ali, et al. "Analysis of Energy Harvesters for Highway Bridges." Journal of Intelligent Material Systems and Structures 22(16) 1929-1938. 2011.

Anton. "Multifunctional Piezoelectric Energy Harvesting Concepts." Doctor of Philosophy Thesis, Virginia Polytechnic Institute and State University, April 2011.

Cattermole, Tannith. "Mobile Phones Charged by the Power of Speech." September 20, 2010. Gizmag. http://www.gizmag.com/mobiles-powered-by-conversation/16417/ Accessed 12/12/2012.

Cook-Chennault. "Piezoelectric Energy Harvesting: A Green and Clean Alternative for Sustained Power Production." Bulletin of Science, Technology, & Society, Vol 28, No 6 Dec 2008 pp 496-509.

Davis, Stacy; Diegel, Susan; Boundy, Robert. "Transportation Energy Data Book" Ed. 31. July 2012, Oak Ridge National Labs ORNL-6987.

Edery-Azulay, Lucy. "Innowattech: Harvesting Energy and Data; A Standalone Technology." Israel National Roads Company, Ltd. First International Symposium. The Highway to Innovation, 1-3 November 2010. Tel Aviv, Israel.

"Evaluation of Energy Harvesting Technology for Use on Oregon Roadways." FY 20145 Research Problem Statement. ODOT Research Section, Salem OR.

Fourie, D. "Shoe Mounted PVDF Piezoelectric Transducer for Energy Harvesting." MIT. 2009.

Genziko RPG product brochure, technical data. 2012.

Guigon, et al. "Harvesting Raindrop Energy: Theory." Smart Mater. Struct. 17 (2008) 015038 (8pp).

Hemsel, T., Wallaschek, J. "Survey of the Present State of the Art of Piezoelectric Linear Motors." Ultrasonics, 38 (2000) 37-40.

Hill, D. "Return on Investment for Structural Health Monitoring Systems in Wind Turbine Blades." DNV Report No. 2010-9509, December, 2010.

Horowitz, et al. "A MEMS Acoustic Energy Harvester." J. Micromech. Microeng 16 (2006) S174-S181.

"Innowattech: Harvesting Mechanical Energy from Roadways to Produce Electricity." Kurzweil, Accelerating Intelligence. October 25, 2011. http://www.kurzweilai.net/innowattech-harvests-mechanical-energy-from-roadways Accessed 12/10/2012.

Innowattech Website. www.innowattech.com Accessed 1/3/2013.

Kuntsal, Ender. Channel Technologies. Verbal discussion 1/14/2012.

"Israeli Energy Startup Turns Traffic into Source of Electricity." Reuters, Mar 10 2009. Haaretz online. http://www.haaretz.com/news/israeli-energy-start-up-turns-traffic-into-source-of-electricity-1.271824.

Lazaru, Jon. Oregon Department of Transportation. Phone conversation 1/17/2013.

Li, et al. "Development of a Biomechanical Energy Harvester." Journal of NeuroEngineering and Rehabilitation 2009 6:22. DOI: 10.1186/1743-0003-6-22.

Lim, et al. "Design and Performance of Miniaturized Piezoelectric Step-Down Transformer." Journal of Electroceramics. Vol 13, Issue 1-3 July 2004.

Milgrom, Charles. Innowattech. Phone conversation, 1/24/2012.

MIL-STD-1376B, Military Standard: Piezoelectric Ceramic Material and Measurements Guidelines for Sonar Transducers. February 24, 1995. [NO S/S DOCUMENT].

Moskowitz, Ira. "Israel's Innowattech to Provide Renewable Energy for Highway Signs in Italy." http://www.greenprophet.com/2010/05/israel%E2%80%99s-innowattech-to-provide-renewable-energy-for-highway-signs-in-italy/. Assessed on 1/29/2013.

OpenEI: Open Energy Info. http://en.openei.org/wiki/Transparent_Cost_Database. Accessed January 1, 2012. National Renewable Energy Laboratory (NREL), Open Government Initiative, US Department of Energy.

POWERleap Technologies product brochure, technical data. 2012.

Priya, Shashank. "Advances in Energy Harvesting Using Low Profile Piezoelectric Transducers." J. Electroceram (2007) 19:165-182.

Sathiyamoorthy, Bharathi. "Hybrid Energy Harvesting using Piezoelectric Materials, Automatic Rotational Solar Panel, Vertical Axis Wind Turbine." Procedia Engineering 38 (2012) 843-852.

Sodano, et al. "A Review of Power Harvesting from Vibration using PiezoElectric Materials." Shock and Vibration Digetst VOl 36, No 3 May 2004.

Sodano, et al. "Estimation of Electric Charge output for Piezoelectric Energy Harvesting." LA-UR-04 -2449, Strain Journal, 40(2), 49-58, 2004.

"Treevolt Piezoelectric Membrane System." http://www.treevolt.com/en/treevolt-piezoelectric-membrane-system.html Accessed 12/13/2012.

Tveter, "Accelerated Wear Testing of High Strength Road Concrete in Norway." Norwegian Masonry and Concrete Research Institute. 1993.

Uchino. "Piezoelectric Actuators 2006: Expansion from IT/robotics to ecological and energy applications." J Electroceram (2008) 20:301-311.

Verbal discussions, Channel Technologies.

Vestel, Leora Broydo. "Harvesting Clean Energy Along the Road." New York Times, July 23, 2009. http://green.blogs.nytimes.com/2009/07/23/harvesting-clean-energy-along-the-road/ Accessed 12/10/12.

Vullers, et al. "Micropower Energy Harvesting." Solid State Electronics 53 (2009) 684-693.

Walsh, et al. "Piezo Power." Digital Safari Greenbizz Company Business Plan Competition, 2011.

Willoughby, Kim. Post Construction & Performance Report, Experimental Features WA 03-04, 04-01, and 05-04, Studded Tire Wear Resistance of PCC Pavements, Contract 6620 I-90 Argonne Road to Sullivan Road MP 286.91 to 292.38. Washington State Department of Transportation. 2007.

Wischke, et al. "Vibration Harvesting in Traffic Tunnels to Power Wireless Sensor Nodes." Smart Mater. Struct. 20 (2011) 085014 (8pp).

Xiong, et al. "New Technologies for Development of Renewable Energy in the Public Right-of-Way". DTFH61-10-C-00016. FHWA 9th Quarterly Report, Virginia Tech. October 2012.

Xu, et al. "Preparation, Properties, and Application Research of Piezoelectric Traffic Sensors." Procedia Engineering 27 (2012) 269-280.

Waterbury, Wright. "Evaluation of the Consultant Report: Assessment of Piezoelectric Materials for Roadway Energy Harvesting, Cost of Energy and Demonstration Roadmap." January 31, 2013.

GLOSSARY

Abbreviation/Acronym	Definition
AC	Alternating Current
ASTM	American Society for Testing and Materials
BOS	Balance of System
CHP	Combined Heat and Power
DC	Direct Current
DNV KEMA	DNV KEMA Energy and Sustainability
DOE	Department of Energy
DOT	Department of Transportation
EIA	Energy Information Administration
FEA	Finite Element Analysis
FHWA	Federal Highway Administration
ft	Foot
Ge	Germanium
Hz	Hertz
IEA	International Energy Agency
J	Joules
km	Kilometer
kph	Kilometer per Hour
kW	Kilowatt
kWh	Kilowatt Hour
Lbs	Pounds
LCOE	Levelized Cost of Energy
mA	Milliampere
MHz	Mega Hertz
MEMS	micro-electromechanical systems
MJ	Microjoules
Mm	Millimeter
MPa	Megapascal
mph	Miles per Hour
MW	Megawatt

Abbreviation/Acronym	Definition
MWh	Megawatt-Hours
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
ODOT	Oregon Department of Transportation
psi	Pounds per square inch
PV	Photovoltaic
R&D	Research and Development
RMS	Root Mean Square
ROI	Return on Investment
SHM	Structural Health Monitoring
Si	Silicon
V	Voltage
VMT	Vehicle Miles Travelled
W	Watts
Wh	Watt-hour

APPENDIX A:
Piezoelectric Energy Harvesting Demonstrations

Innowattech

Innowattech is the most notable company to implement piezoelectric-based energy harvesting on a bulk, macro scale.

http://www.innowattech.co.il/

The system is installed by Innowattech in Israel. The piezo harvesters are imbedded 5 cm below the surface of the road. It is projected that increasing the system size to 1 km would produce 200 kWh while a four-lane highway would produce about one MWh. Traffic studies for the Ayalon Highway, coastal highway, and Trans-Israel Highway examined the energy potential. The Israeli test was conducted in 2009.

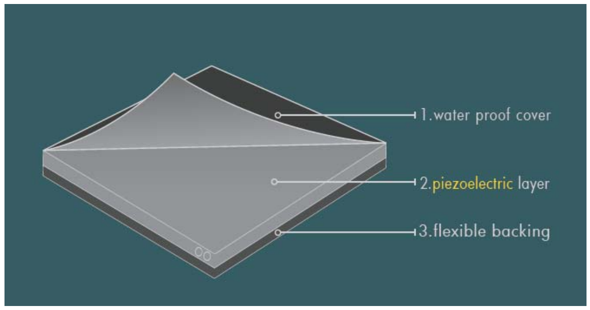
Innowattech was selected by Impregilo SpA, an Italian infrastructure and civil engineering contractor's energy provider for lighting road signs on the Venice-Trieste highway in Italy. This contract is part of a €225 million upgrade of the highway that began in 2010 and is expected to be completed in 2013. The generators developed at Innowattech will be placed beneath the highway's upper asphalt layer. The electrical energy generated by the technology is created during the movement of vehicles on the road and is stored via dedicated electrical systems. This will supply electrical energy for lighting Variable Message System signs. Drivers will read traffic reports on electronic signs which will be powered by electricity from the drivers' own vehicles[15].

PiezoPower, Piezoelectric Floors

London Club Surya and Rotterdam WVatt have piezo floors to harvest energy from dancers. The floor system is engineered with springs and a series of crystal and ceramic blocks. In the clubs, this can supply up to 60 percent of the club's energy needs. Each person can produce between 5-20W. The East Japan Railway Company worked in conjunction with Keio University to imbed piezo in the floor of terminals and train stations. This is also an opportunity for health and fitness clubs. Digital Safari Greenbizz Company is aiming to capitalize on the technology by building piezoelectric floors and quotes Time Magazine by indicating 1 watt per breath, 70 watts per step are possible. The product is called *Electroturf*. Piezo Power is the company that sells the product, estimating 1500 ft^2 for $2250, or $1.50/ft^2. The product is designed as subflooring in 3'x5' tiles. It is estimated that about 25 percent of the 70 W in a single step is captured (17.5 W). The piezoelectric material is Rochelle salt. The Piezo Power business plan indicates that Rochelle salt costs $1 per metric ton and is sourced from Pinhuangdao Bright Chemical Company.

[15] http://www.greenprophet.com/2010/05/israel%E2%80%99s-innowattech-to-provide-renewable-energy-for-highway-signs-in-italy/. Assessed on 1/29/2013.

Figure 27: Piezo Floors



POWERleap Inc.

POWERleap Inc. is located in San Francisco, California, and is in a partnership with Treevolt located in Columbia. For asphalt roadways, the harvesters are membrane-based designs containing recycled butyl-propene where full sheets of harvesting devices are fully-embedded under the top layer of asphalt. For concrete, the harvesters are a block-based design that is partially-embedded into the roadway such that pressure from passing vehicles is directly transferred to the devices. The manufacturer's literature on the devices indicates that a 1.0 km length of roadway with 600 vehicles per hour and 6,000 Treevolt harvesters can yield approximately 720 kW. The devices can also be equipped with data monitoring capabilities that can collect roadway and vehicle data. The devices can transmit the data through wireless communications to a cloud-based platform so that the data can be accessed at any time from any internet-enabled device[16]. Floor-based power generation from POWERleap products have shown 10 W generated from a footstep with a 2.2 volt potential across the functional material. This implies approximately 4.5A generated from the unit.

Figure 28: Treevolt Devices being Tested in Columbia (left) and POWERleap Data Harvesting (right)

[16] POWERleap Technologies product brochure, technical data. 2012.

KCF Technologies

Off-the-shelf products are designed to sense and harvest energy from vibrations, such as those available from KCF Technologies. KCF is developing vibration energy harvesting devices to power wireless sensor nodes. The device scavenges vibration energy from a host structure, eliminating battery replacement for industrial sensors. They have also developed a self powered wireless sensor kit that simultaneously monitors vibration losses while using the vibrations to power the distributed sensor network. Freely available vibration energy is captured and used as the only power source.

Oregon Department of Transportation

In late 2008 and early 2009, with the success of the Oregon Solar highway, the Oregon Department of Transportation (ODOT) evaluated harvesting energy from roadway vibrations. Vendors claimed to be able to capture energy with piezoelectronic devices installed into the pavement. The ODOT did not commit to installing the devices because there was no United States-based vendor at the time. Other vendors offered energy harvesting from a combination of solar and 'speed-bump' devices which depress with the vehicle weight. The ODOT elected to pursue a solution which could be installed and keep the road surface flat for highway traffic[17].

Since then, a United States company named POWERleap has partnered with the Colombia-based company Treevolt and entered the market. In 2012, Oregon State University submitted a new research proposal to the ODOT to study piezoelectric harvester's reliability and maintenance requirements[18]. The application was rejected in the first round of evaluation because the evaluation committee was concerned about the maturity of the product, citing FHWA's report by Eric Weaver in 2012.

Channel Technologies Inc.

Channel Technologies Inc. (Santa Barbara, California) manufactures the ceramics that have been investigated by Innowattech as a United States supplier for materials. Channel Technologies had a low volume supply agreement with Innowattech to investigate their material as the functional element for the Innowattech devices. Presently, Innowattech does not use Channel Technologies for their main product or development. It has been said that the piezoelectric disc cost should be targeted at about $1/disc[19].It has also been stated that the lifetime of the piezoelectric material is expected to be 30 years, but the lifetime of the ancillary pieces of the energy harvesting device may or may not reach the lifetime of the disc itself. One of the challenges that Channel Technologies faced early on in discussions with Innowattech was meeting the strength and durability requirements for the roadway or railway.

[17] Lazarus, Jon. Oregon Department of Transportation. Phone conversation 1/17/2013.

[18] Gambatese, John. "FY 2014 Research Problem Statement: 14-047 Evaluation of Energy Harvesting Technology for Use on Oregon Roadways." Oregon Department of Transportation. http://www.oregon.gov/ODOT/TD/TP_RES/docs/stage1/2014stageone/14_047_Energy_Harvesting.pdf. Accessed 12/11/12.

[19] Verbal discussions, Channel Technologies.

Virginia Tech

Virginia Tech is managing a three year project with a contract amount of $1 million. [20] The United States DOT funded project is investigating the use of piezoelectric materials for roadway energy harvesting. The project just completed its 9th quarter. Presently the data indicates that the total system voltage ranges from 400-700V and 0.2-0.35 mA per unit, with power pulses of 0.1-0.2 seconds. Tested in heavy truck traffic at about 40 mph, the demonstration targets a 4,000 vehicle per day (166 vehicles/hr) traffic flow rate[21].

It is shown in the Virginia Tech reports that the harvester developed was of their own design. The power output per unit is low compared to vendor claims, and the lab-based design may account for the low power output. Commercial designs may incorporate linkages for mechanical advantage to increase force on the piezoelectric stacks and improve power output, and therefore it may not be fair to say that the Virginia Tech unit is representative of commercial design.

Table 15: Summary of Known Demonstrations and Their Approximate Cost

Demonstration	Estimated Project Cost
Innowattech, Israel	$650,000/km
Virginia Tech, US FHWA	$1 million

Genziko

Vendor information from Genziko[22] estimates installation costs at $0.40/W and LCOE of $0.06-$0.08/kWh. These estimates are considerably more optimistic than what has been implied in discussions with other vendors. The lifetime estimate of 20 years is consistent with what is expected, however there appear to be no significant differences in the system construction as compared to other technologies proposed here, Therefore, the same sensitivity factors would apply: (1) claimed power generated, (2) lifetime, and (3) capital cost. The sensitivity to the first factor, however, is likely much greater due to the reasons explained below.

The low LCOE quoted by Genziko is likely attributed to high power density claims and a claimed lower cost than competing sources. On a six-lane freeway with 2,250 vehicles per hour per lane (about 54,000 vehicles per day) they claim a power output of 51 MW per km. They also provide an estimate of capacity factor near 32-42 percent. Since the capacity factor number is contingent on road traffic, it would imply that there are power generation events occurring approximately every three seconds, or 20 events per minute, or 1,200 events per hour. Since every vehicle represents two events (two axles per vehicle), this would correspond to 600

[20] Xiong, et al. "New Technologies for Development of Renewable Energy in the Public Right-of-Way". DTFH61-10-C-00016. FHWA 9th Quarterly Report, Virginia Tech. October 2012.

[21] Xiong, et al. "New Technologies for Development of Renewable Energy in the Public Right-of-Way". DTFH61-10-C-00016. FHWA 9th Quarterly Report, Virginia Tech. October 2012.

[22] Genziko RPG product brochure, technical data. 2012.

vehicles per hour which is consistent with the low estimate for *collection* roads or two-lane roads in the Genziko marketing documents.

Taking this calculation further, the 600 vehicle per hour estimate corresponds to a 13.6 MW/km power density. Assuming 6,000 units per km[23], each unit is contributing a continuous power output of 0.002 MW (2kW). Recall that the Virginia Tech demo recorded about 0.08-0.14 W for every wheel impact event, or about 10,000 times less. In order for this disparity to be possible, some differentiating characteristic of the Genziko product must harvest energy more efficiently than the competing technologies.

The differentiating characteristic of the Genziko product appears to be a claim that the unit continues to generate electricity after the initial wheel impact, indicating a resonant or persistently vibrating energy harvesting technology that is unlike the single impulse compressive energy generation system designed by Innowattech (Figure 12). In the Genziko product, the initial impact generates energy but a lasting resonance or decaying vibration continues to generate. Such technologies may be based upon arrays of micro-cantilever beams similar to what is used in micro-electromechanical systems (MEMS) and structural health monitoring (SHM) systems.

Compared to the data from ODOT and the press releases from Innowattech, the Genziko traffic flow rate (2250 vehicles per hour) is about 3-13 times greater. However the power claim (51 MW) is 70- 500 times greater than what is claimed by ODOT and Innowattech, which are more optimistic than what has been demonstrated by Virginia Tech.

The information provided does not provide much technical detail about the functional piezoelectric or ceramic materials that convert vibration or stress into energy, so it is difficult to assess the exact intellectual property or technology advantage that would lead to these performance metrics, but it is likely vibration-based.

The difference in power metrics is illustrated in the comparison table below.

Table 16: Difference in Power Metrics

Parameter	Genziko	ODOT	Innowattech	Berkeley and Virginia Tech
Power per km (single lane)	13-51 MW	486 kW	100-200 kW	0.0018-0.5 kW
Vehicles per hour (single lane)	600-2250	600	600	600
kW per km per vehicle per hour	21.6-22.6	0.81	0.16-0.3	0.000003 – 0.00083

Genziko has not provided information about railways.

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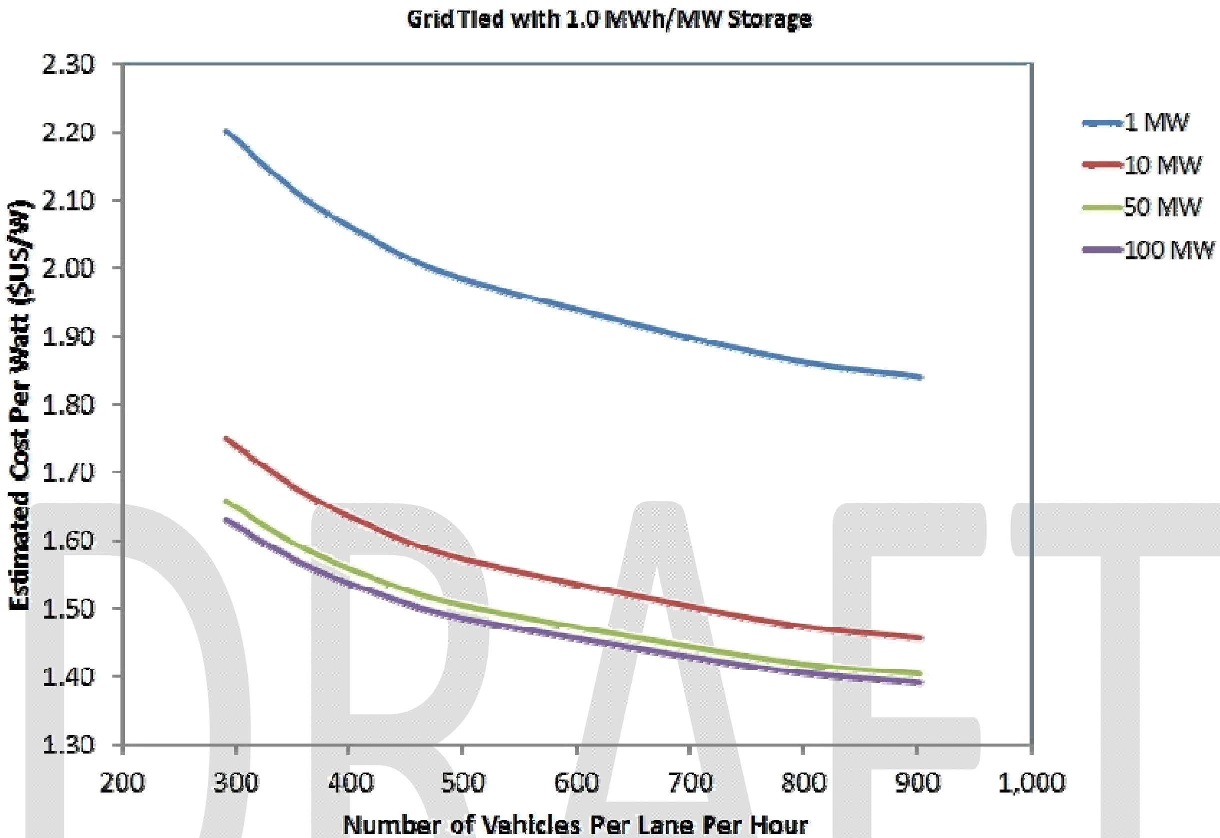
[23] Based on the POWERleap/ODOT estimates.

The interconnect between the Genziko power system and the grid implies a grid-tied inverter system which is likely lower cost than a battery-based energy storage system, thought it still has provisions for energy storage. The maturity of these technologies may not be off-the-shelf, as indicated by Table 16.

Table 17: The Genziko product is still not quite mature, as it can be seen that the material and the device are admittedly still under development.

Technology	Inventor(s)	Date(s)	Patent	Verification Procedures
Material	Near	1991-1999	To be	DoD-1376B(SH)[3]
Nano Process	Dawson[1]/Swartz[1]/ Near	1988-1996	Patented + Potential	DoD-1376B(SH)[3]
Forming	Kiggans[2]/Near	1998-2003	--	DoD-1376B(SH)[3]
Processing	Near	1987-1994	--	DoD-1376B(SH)[3]
Configuration	Near	1995-2009	Application	Actuation [4] Harvesting [5]
RPG	Near	1975-2011[6]	To be	--

Figure 29: Genziko Estimates for Capital Costs based on Storage Capacity



APPENDIX B:
Literature Evaluation

1. Source: Cook-Chennault. "Piezoelectric Energy Harvesting: A Green and Clean Alternative for Sustained Power Production."

   Subject Matter Evaluation:

   The peer-reviewed paper connects the capability of the technology with state and federal initiatives to produce clean and renewable energy. Table 3 in this paper illustrates a wide range of applicable piezoelectric technologies that can be cross-referenced to the roadway application in order to verify the power density, energy density, and performance metrics. The document also demonstrates data concerning the optimum harvesting of energy.

   Objectivity: This is a peer-reviewed scientific article and is therefore considered to be objective.

   Persuasiveness: The article is peer-reviewed and not intended to be persuasive, but informative.

   Value: Power density metrics, optimal vibration frequencies (between 100-120 Hz), dimensions of piezoelectric devices, total power generated (as a function of size), and additional energy metrics are provided. This is peer-reviewed data that can be immediately cross-referenced to the commercial claims stated in other sources for the purpose of validation. The document also describes critical development needs and technical challenges preventing the immediate adoption of piezoelectric materials for macro-scale energy production.

2. Source: Xiong, et al. "New Technologies for Development of Renewable Energy in the Public Right-of-Way."

   Subject Matter Evaluation:

   This report to the Federal Highway Administration (FHWA) concerns a demonstration of piezoelectrics in roadways in Virginia. Study of the durability of the materials is included, and the study mentions Innowattech. The harvester appears to degrade in performance when exposed to water and the demonstration mentions degradation of a silicone layer which also impacts the effectiveness of the device to harvest mechanical energy. There is some valuable data in the report, such as the use of a controlled testing apparatus with a 600 lb load and wheel speed of 7.5 mph and 15 mph to generate electricity and store power in a charged capacitor. The capacitor energy is directly proportional to the voltage generated in the piezoelectric device. The report confirms that there is a proportional relationship to load time and power generated. The report confirms a demonstration being performed with eight field devices at the Troutville weigh station on interstate I-81N in the bypass lane. The traffic pattern is mostly trucks, estimated in quantities of 4,000 per day, traveling at 40 mph. Patterns were cut out to install the devices, indicating that at least for this demonstration, removal of an entire road section was not required. The devices measure approximately 1 ft^2 and generate approximately 400-700 V with each truck impact and 0.2-0.35 mA. The trucks generally have four axles passing over the devices representing short pulses of power measuring ~0.1 s. Therefore, the energy generated is 400V *0.2mA * 0.1s = .008 Wh per tire impact per unit, at a minimum. The power arrives in pulses corresponding to wheel impact averaging .08 W or more. The report estimates that the maximum instant power is .14 W. The capacity factor in this case per unit over an 8 second interval appears to be ~0.4/8 = 0.05.

Objectivity: The report to the FHWA is written by the Principal Investigator and appears to be a physically demonstrated evaluation of the technology.

Persuasiveness: The article is a statement of a series of facts and is therefore not intended to be persuasive; however, the data is demonstrable and therefore valuable to an objective assessment of the technology.

Value: Durability, performance, load, traffic, and installation data are all provided to a high level of detail with useful data and power metrics.

3. Source: "Evaluation of Energy Harvesting Technology for Use on Oregon Roadways."

   Subject Matter Evaluation:

   This informational document explains strategic research initiatives guided by the ODOT and explains the application of piezoelectrics and also names some companies of technologies explained in this report, such as POWERleap Inc. There is intriguing data in the source which can be used for cross validation: a 1.0 km length of road with a traffic flow of 600 vehicles per hour (10 per minute) with 6,000 Treevolt harvesters can yield approximately 350,000 kWh per month.

   Objectivity: The ODOT evaluation is inherently intended to be objective as it guides investment by the state. However, the claims about the POWERleap Inc. technology are not clearly identified as third party validated.

   Persuasiveness: The explanation of the technology is compelling and persuasive and shows potential.

   Value: The data concerning POWERleap Inc. is valuable and will be used in the report as part of the evaluation. It also demonstrates that ODOT has intentions to build a 1.0 km roadway demonstration.

4. Source: Ali, et al. "Analysis of Energy Harvesters for Highway Bridges."

   Subject Matter Evaluation:

   The paper is primarily concerned with Structural Health Monitoring (SHM) and using piezoelectric devices to power the wireless sensor network. References to Sodano have been used in other DNV KEMA research. This appears to be a definitive reference. It illustrates that in a bridge, the load is moving which changes the deflection and resonance frequency over the length of the bridge. The paper calculates the displacement of the beam and the frequency as a function of vehicle speed and load. Energy harvesting with induction-based mechanisms was explored in addition to piezoelectrics. After the derivation of the mathematics to derive critical parameters such as load, frequency and optimized location of the harvesters, a numerical example is provided which cites some interesting metrics. First, a typical vehicle speed of 25 m/s corresponds to a fundamental excitation frequency for a 25 m bridge of 0.5 Hz. Harvester locations are at integral fractions of bridge length, for example, L/2, L/3, and L/4. The energy harvested for a 2.5 g energy harvesting device is up to 18 MJ per vibration.

Objectivity: The authors are from Swansea University and appear to be objective and without commercial bias.

Persuasiveness: The paper is not intended to be persuasive, although it highlights useful data which indicates technical feasibility for using vibration-based energy harvesting to power SHM devices.

Value: The description of the moving load problem is useful because it is transferable to the problem at hand, for example, imbedding piezoelectric materials into a roadway. The moving load problem highlights that claimed efficiency for a piezoelectric panel device is largely dependent on its orientation and possible aspect ratio if harvesting direct vibrational energy from a roadway. The low frequency vibrations of the bridge seem to be best suited for an induction type energy harvester and are less relevant for piezoelectrics. This is also a recent paper which includes data for more recent technology.

5. Source: Priya, Shashank. "Advances in Energy Harvesting Using Low Profile Piezoelectric Transducers."

   Subject Matter Evaluation:

   The paper explains the need for harvesting energy from vibrations and the energy needs of various electronic devices. It explains how vibration energy can power these devices and how they compare across an equivalent spectrum in energy density and power density terms.

   Objectivity: The paper is peer reviewed and therefore represents an evaluation with reasonable objectivity.

   Persuasiveness: The paper illustrates the viability of vibration-based energy harvesting. However, it does not fully address the use of vibration energy harvesting on a macro scale.

   Value: There is a lot of background information on energy density of energy storage and power devices, as well as data on energy generated from energy sources such as human power, temperature gradients, and pressure vibrations. The paper also illustrates three methods to harvest energy from vibrations; piezoelectric methods is one of them. This information can be used to cross reference the efficiency and energy generating capabilities of present technologies, and may be used as an objective reference to validate otherwise commercial claims.

6. Source: Kurzweil. "Innowattech: Harvesting Mechanical Energy from Roadways to Produce Electricity."

   Subject Matter Evaluation:

   This web article presents two commercial videos and an explanation of Innowattech's piezoelectric technology. The videos explicitly show animations of vehicles on highways.

   Objectivity: The article appears to be a press release for Innowattech, so it is likely commercially biased.

   Persuasiveness: The technology and the claims are compelling and appear to have technical feasibility, but very little actual data is provided to aid in the validation of the claims.

   Value: Explanation of how the technology is proposed to work is useful and has direct relevance to the subject matter of this evaluation.

7. Source: "Treevolt Piezoelectric Membrane System."

   Subject Matter Evaluation:

   This website for the manufacturer of the technology licensed by POWERleap Inc. shares data claims. Claim: The average energy generated by 1 km of installed piezoelectric membrane is in the range of 400-600 kWh for an estimated 200 to 400 vehicles in 16 hours of traffic.

   Objectivity: This is a vendor website so there is a conflict of interest in the persuasive claims.

   Persuasiveness: The claims are persuasive.

   Value: More data is provided to cross-validate with other claims provided in this document.

8. Source: Walsh, et al. "Piezo Power."

   Subject Matter Evaluation:

   This document is a business plan for a company called "Piezo Power" which intends to market flooring materials to harvest energy from pedestrians and possibly mobility traffic. The document contains energy generation and cost data for the product in addition to projections of sales of the product and growth of the company.

   Objectivity: This document is a business plan and therefore presents forward looking statements that are not easily verified.

   Persuasiveness: The affordability of the product is persuasive, and if translated to the roadway problem, presents a compelling argument for the cost effectiveness of piezoelectric energy harvesting.

   Value: The business plan mentions that 70 watts per human step are generated and that the system is 25 percent efficient, harvesting 17 watts per step. The Electroturf product can harvest. Costs are estimated at $2,250 per 1,500 square feet of material, using 3'x5' tiles. These cost and efficiency metrics can be compared to the roadway application and determine two things: the difference in cost between this simpler construction and roadway construction, as well as validate claims about efficiency and power density.

9. Source: Edery-Azulay, Lucy. "Innowattech: Harvesting Energy and Data; A Standalone Technology."

   Subject Matter Evaluation:

   The presentation is given by Innowattech with claims about performance and demonstration data.

   Objectivity: This is a presentation given by Innowattech which is one of the most notable companies selling piezoelectric energy harvesting technology. The presentation is aimed at advertising for the product.

   Persuasiveness: The data is persuasive.

   Value: Roads application claim: 200 kWh/h for 600 vehicles per hour at 72 km/h speed, one km section. Railway application claim: 120 kWh/h for two generators in every "sleeper", average railway movement of 300 loaded wagons per hour.

10. Source: "Israeli Energy Startup Turns Traffic Into Source of Electricity."

    Subject Matter Evaluation:

    Innowattech, an energy company affiliated with Israel's Technion Institute of Technology, said special generators placed under roads, railways and runways can harvest enough energy from passing vehicles to mass-produce electricity.

    Article, press release for Innowattech.

    Objectivity: It is a review article but contains data and input from Innowattech and the companies involved, so there may be some conflict of interest in the data.

    Persuasiveness: Article is persuasive but reveals high capital cost for electricity.

    Value: Uri Amit, chairman of Innowattech, said the company's technology will be the largest application of piezoelectrics to date, with a single 1-km (half-mile)-lane of highway providing up to 100 kW of electricity, enough to power about 40 houses. Innowattech chairman Amit said the current cost for fitting a kilometer (half-mile) of one lane of highway is about $650,000, with a cost of $6,500 per kilowatt. He said when mass production begins, the price could drop by two thirds, making the system even cheaper than solar energy systems.

APPENDIX C:
Data Summary

Data from the literature sources has been extracted in order to establish relevant baseline metrics and consolidate them into common units. The raw data is shown in Table 17. An additional column addressing the objectivity of each data source is also included. There are some critical parameters that can be extracted from the data and consolidated into common units. These are shown in Table 18.

Table 18: Raw Data Extracted from Literature Review

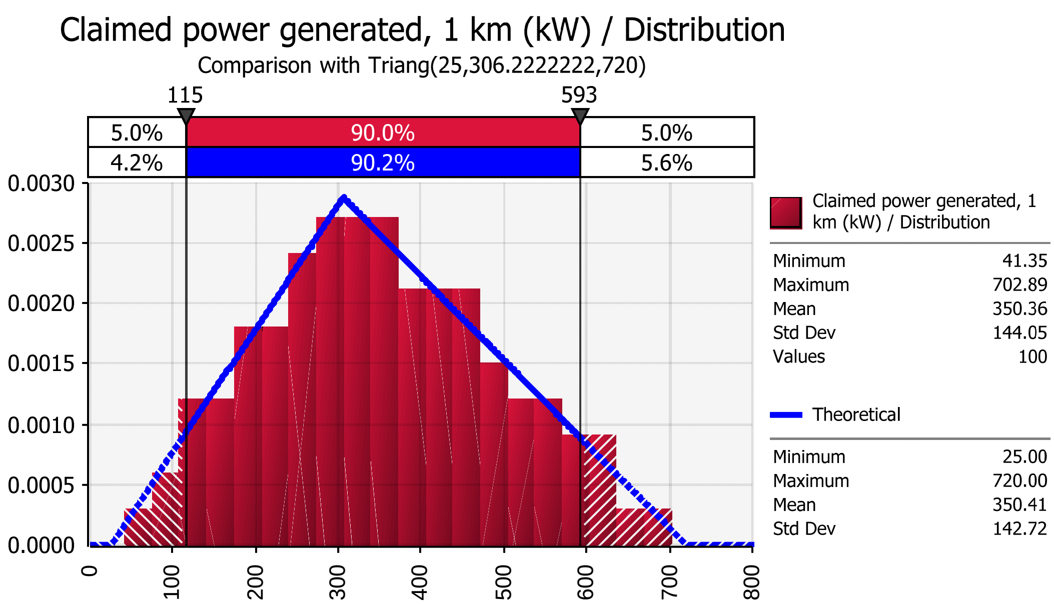
Parameter	Low Estimate	High Estimate	Source	Objectivity Ranking (1=low, 3=high)
Optimal vibration frequencies (Hz)	100	120	Cook-Chennault	3
Tested wheel speeds (mph)	7.5	15	Virginia Tech	3
Voltages (V)	400	700	Virginia Tech	3
Amperage (mA)	0.2	0.35	Virginia Tech	3
Power Duration (s)	0.1	0.2	Virginia Tech	3
Maximum measured power per event, (W)	0.08	0.14	Virginia Tech	3
Virginia Tech Traffic Flow speed (mph)	40		Virginia Tech	3
Virginia Tech Traffic Flow rate (vehicles per day)	4,000		Virginia Tech	3
Oregon DOT Traffic Flow Rate (vehicles per hour)	600		Oregon DOT	3
Energy Generated for 1.0 km, Oregon (kWh/month)	350,000		Oregon DOT	3
Number of harvesters, Oregon DOT	6,000		Oregon DOT	3
Energy harvested for bridge mounted devices, per vibration (microJ)	18		S.F. Ali, et al	3
Vehicle speed for micro harvesters (m/s)	25		S.F. Ali, et al	3
kW per km	0.0018		Berkeley	3
units per km		10,000	Berkeley	3
Axles per vehicle	2	8	Berkeley, Oregon	3

Parameter	Low Estimate	High Estimate	Source	Objectivity Ranking (1=low, 3=high)
Target Cost of piezoelectric material (per unit)	$1		Channel Technologies	2
Energy generated in 1 km stretch of road (kWh)	400	600	POWERleap, Treevolt	1
Time span of energy measurement (hr)	16		POWERleap, Treevolt	1
Traffic flow rate, POWERleap (vehicles/hr)	12.5	25	POWERleap, Treevolt	**1**
Vehicles per hour	600		POWERleap	1
Power rating (kW)	720		POWERleap	1
Length of energy harvesting section (km)	1		POWERleap	1
Number of harvesters per 1 km	6,000		POWERleap	1
Power per unit per impact (W)	10		POWERleap	1
Power generated per sq ft, foot traffic (W/ft^2)	1.13		Piezo Power	1
Cost per square foot, foot traffic ($/ft^2)	$1.50		Piezo Power	1
Power rating, 1.0 km (kW)	200		Innowattech	1
Power rating, train (kW)	120		Innowattech	1
Traffic flow rate (vehicles per hour)	600		Innowattech	1
Vehicle speed (kph)	72		Innowattech	1
Train speed (wagons/hr)	300		Innowattech	1
Size of each unit (ft^2)	1		Virginia Tech	3
Power per km (kW)	100		Innowattech, Haaretz article	1
Cost per km ($)	$215,400	$650,000	Innowattech, Haaretz article	1
LCOE ($/kWh)	0.06	0.08	Genziko	1
Lifetime (y)	20		Genziko	1
Installation cost ($/W)	0.4		Genziko	1
Capacity Factor	0.32	0.4	Genziko	1
Vehicles per hour	600		Genziko	1
Power Density (kW/km)	13,600		Genziko	1
Long dimension of unit (m)	0.45		Genziko	1

Parameter	Low Estimate	High Estimate	Source	Objectivity Ranking (1=low, 3=high)
Short dimension of unit (m)	0.3		Genziko	1
Genziko Units per km	2,222	3,333	Calculated from Genziko	1
Number of harvesters	9,800		Calculated from Virginia Tech	1

The information in Table 18 sorts the numbers by source. In the tables shown, the data is organized into a probability distribution for a Monte-Carlo financial analysis. The far right column labeled *Distribution (mean shown)* indicates that the value in the column is the mean of a distribution of values. The distribution of values is a triangular probability distribution created from the spread of values collected from the data, extracting the minimum, average, and maximum value. An example of one of the probability distributions is shown in Figure 30 (estimation of the claimed power generation).

Figure 30: Example Probability Distribution Generated from the Range of Numbers Extracted from the Literature Review



The advantage of collecting the data in this way is to account for a span of uncertainty and incorporate this uncertainty in the financial outcome. The final calculation of the cost of energy will include scenarios such as when all of the minimum values align, for example, or when all of the maximum values align, and the probability of that occurring given the known data from the literature review. More of this will be explained in the cost of energy assessment.

Table 19: Report Numbers Consolidated into Common Units

	Va Tech	Innowattech		ODOT	Ali	POWERleap/Treevolt		Distribution
Vehicles per hour	166.67	600		600		12.5	600	336.11
Vehicle speed (mph)	40	44.64			55.75			47.52
Claimed power generated, 1 km (kW)		200	100	486.11		25	720	350.41
Number of harvesters, 1 km				6,000			6,000	6,000
Cost per km		$214,500	$1,086,000					$650,250

The data in Table 19 is calculated from Table 18. Again, probability distributions are used and these will act as inputs for the cost of energy calculation where relevant. The references are noted and will be connected (by number) to the updated final literature list in the final report.

Table 20: Additional Parameters Estimated from the Literature Summary

Calculated Parameters	Probability Distribution Mean	Calculation
Installed Cost per harvester ($)	$108.38	Installed cost per km divided by number of units per km
kW per harvester	0.06	kW per km divided by number of units per km
kW per mph	7.37	kW divided by vehicle speed
Spacing Interval (per m)	6.00	1,000 meters (1 km) divided by number of harvesters
Length of unit (m)	0.17	1 meter divided by number of harvesters per meter
Units per km	6,000	Direct from literature
Length of installation (km)	1	Direct from literature

This data will be used to calculate the cost of energy. The cost of energy begins with a simple procedure to estimate the time to payback the original investment. For example, if 1 km of roadway is built at a cost of $650,000, then the energy generated per day (kWh) multiplied by the sale price of energy per kWh ($/kWh) will be revenue used to pay back that investment. The time to payback will be determined by how much energy is produced and the sale price of that energy. This is a simple payback calculation but does not include interest rates. An additional net present value calculation will also be provided with appropriate discount rate assumptions.

The Monte Carlo method will provide additional information such as what the minimum tolerable electricity revenues need to be in order to provide reasonable payback, what the lifetime of the system shall be, or what conditions shall exist in order to ensure a payback over a certain time frame (three or five years, for example). In addition to this information, a sensitivity analysis will provide sensitivity indicators which will be the critical variables that influence the calculation, such as vehicle speed or vehicles per hour, for example.

The analysis can be progressively more detailed by using this payback technique to calculate the net present value of the investment with respect to a future time or date.

Appendix D:
Evaluation Criteria

What would an evaluation of the technology look like?

Any evaluation should include an analysis of several critical parameters and an assessment of the impact of these parameters on the performance of the energy harvesting system. The analysis can include demonstration, lab scale verification, and accelerated lifetime tests. These variables will examine the effect of piezoelectric materials and devices on the longevity or maintenance of the roadway, main degradation characteristics of the composite system, energy generated as a function of vehicle speed, weight, and traffic volume, and the reliability of energy generated. These critical parameters are described in more detail below.

Many of these tests and examination methods have commonality between roadway and railway installations, although there are some factors that are more application-specific and they will be described as such.

Module Power Output

First and foremost, the power output of an individual module must be quantified. The module output in the uninstalled condition will be different than what it can replicate in the roadway. Layers of asphalt and underlying substrate will affect the response of the module to stimulus. Quantifying these effects can either be done directly in a simulated installation, or they can be modeled with FEA. Most importantly, the power output should be measured in a real world condition, for example, on a load calibrated to be equivalent to a grid or energy storage connection such that the actual power output is measured.

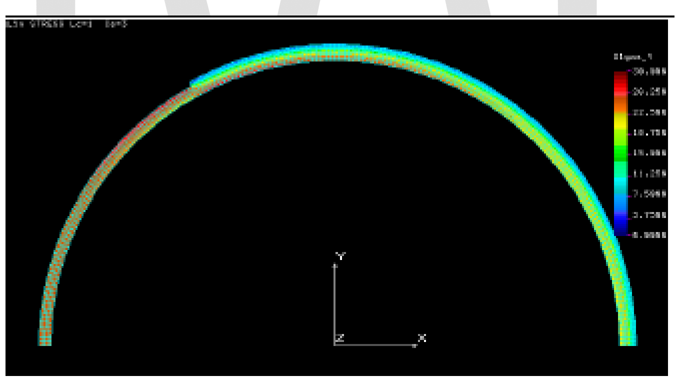
Such an evaluation can be done on a stress frame similar to the Instron frame shown in Figure 31. The device can be installed in the frame and loaded (compressed or cycled) to stimulate the power generation mechanism. Actual power output in the uninstalled condition can be compared against the installed condition to verify performance and quantify the power output per module.

Testing the module in the *installed* condition can be done with a simulated installation or with FEA. The results from the uninstalled test can be modeled in an *installed* condition by replicated the conditions that produced a known wattage, and then modeling material overlays such as asphalt to determine their effect on the forces felt by the power module. The net power output can be calculated in this fashion.

The Instron test frame shown in Figure 31 is equipped with a jig for performing three point or four point bends, and is capable of fatigue cycles. This test frame is located at the DNV KEMA Technology Center (a materials testing lab). Similar machines can replicate cycling at frequencies near 40 Hz and can perform compression or tension tests at 10,000 psi or more. A jig for performing tests on piezoelectric materials can be similarly constructed to quantify power output as a function of load. Adapting a machine for testing piezoelectric materials is technically feasible with the appropriate modifications.

Figure 31: Instron Test Frame at the DNV KEMA Technology Center

Figure 32: Finite Element Models of a Stressed Member with Layered Materials of Differing Moduli



Duration of *Hit* (Power Pulse Duration)

Related to vehicle speed, the rolling wheel over a piezoelectric panel represents a continuous rolling stress that is different than a single *hit* like a step on floor panel. Therefore there is an element of uncertainty in the power generation potential based on the speed of traffic as it has a direct impact on the duration which piezoelectric devices are stressed and thus generating power.

In the roadway application it appears there is a strong dependence on vehicle speed. In the railway application there is less dependence on speed since the train rail acts as an efficient force transfer mechanism.

For the Genziko product, the product literature indicates a different energy harvesting mechanism likely related to resonance at fundamental frequencies associated with traffic. Therefore, the *hit* has a lingering, decaying output not unlike a damped harmonic oscillator.

Energy Transfer and Vehicle Weight

Testing of the module power output provides the vehicle weights needed to maximize performance. The module power provides a maximum baseline against which all other performance metrics may be compared. In early phases, this can be inferred by way of modeling or calculation. In later phases it can be confirmed by demonstration.

The energy of the *hit* will likely vary with vehicle weight because of the energy transferred through the asphalt layer to the piezoelectric system. The asphalt is not a completely rigid material medium and therefore heavier vehicles (such as trucks) will likely transfer more energy to the piezoelectric devices than lighter vehicles (such as cars). There is much data suggesting that trucks impart more energy than cars and the Virginia Tech demonstration targets trucks specifically, presumably because more energy can be harvested.

The angle at which a vehicle tire encounters the piezoelectric device will also affect its output. Since there is significant variability in the track width of vehicles and a high probability that **many vehicles will encounter the devices on a less-than-ideal trajectory** (such as while changing lanes), the output of the system should be analyzed with regard to this uncertainty. The roadway harvesters employ a force multiplication mechanism to account for this uncertainty, but it will have less relevance, for example, if the car or truck changes lanes when passing the region where the harvesters are installed.

Although the ideal piezoelectric device has a limit threshold of the maximum energy it can generate, the nature of the surrounding roadway materials will likely dampen its response and affect the total energy generated. The performance of the system should be studied in the form of **vehicle weight versus power generated**. Such data would inform the operator whether the system is better suited for traffic patterns with heavy vehicles versus passenger cars.

Durability and Lifetime of the Piezoelectric Ceramic

Piezoelectric materials are like other solid state materials in that they will degrade over time, resulting in reduced output and response time. This degradation is relevant to both roadway and railway applications.

Since a demonstration would take some time to produce results, accelerated test methods are recommended to rank the longevity of products in simulated environmental conditions.

Factors that influence degradation are temperature, moisture, stresses greater than the design load, and uneven stresses (bending moments) that can crack and fracture the brittle material. As the piezoelectric degrades, the response frequency will drift, the capacitance of the material will decrease, and the coupling coefficient will change.

Since lifetime of the piezoelectric devices is a major uncertainty, there should be extensive study of the lifetime and durability of the system through accelerated ageing and wear tests.

Modifications of ASTM C627, *Standard Test Method for Evaluating Ceramic Floor Tile Installation Systems Using the Robinson Type Floor Tester*, have been cited as an adequate testing procedure for abrasion resistance of pavements[24] This ASTM test or a modified wear test should be used to rank the wear resistance of the composite piezoelectric-pavement road system against known road wear characteristics and load, as it will help characterize the lifetime which has a direct impact on the cost of energy.

Standards such as MIL-STD-1376 describe the durability characteristics of piezoelectric ceramic materials for defense applications. This standard describes six types of piezoelectric ceramic materials utilized for sonar transducers for the Naval service. This standard also describes the properties of the ceramic compositions for these six types as measured on standard test specimens. The durability specifications and testing requirements would have relevance to a roadway or railway application. These standards address the properties of the ceramic, but not the ageing behavior of the system as a whole.

Durability of System and Components

The functional component of the energy harvesting system is the piezoelectric, however, the associated electronics, frame, and structural components of the piezoelectric devices are also critical to its long term functionality. In a roadway, challenges may exist such as isolating the piezoelectric and its associated electronics from temperature, moisture, and loading effects that are inevitably linked to the harsh environment of the roadway. The auxiliary components of the piezoelectric harvesting devices, such as force multiplying mechanisms, wiring, circuitry, and electronics, would require weather hardening and validation where they can withstand harsh conditions. Tests such as ASTM B117, *Standard Practice for Operating Salt Spray Aparatus*, have been modified to test the weathering performance of materials using ageing acceleration vectors such as temperature, salt water exposure, ultraviolet light exposure, and wet/dry cycles.

For the railway application, the exposure to external weather is applicable and minor modifications to ASTM B117 would be required. However, the buried environment of the roadway implies not only water exposure, but compression forces and material interactions of a different nature than the rail system.

The roadway demonstration data indicates that approximately 5 cm (~2 in) of asphalt is installed over the piezoelectric systems. While these demonstrations are valuable, they do little to indicate the long term viability of the technology. Virginia Tech has noted that waterproofing and water resistance are technical challenges faced by the technology. In addition, there is a question as to whether the piezoelectric substrate impacts the durability of the road system and introduces uneven wear patterns in the upper layer of asphalt. A critical component to understand ageing in these tests is not just wear and abrasion of asphalt, but the combined effect of wear and load and the *rippling* or *dimpling* behavior of asphalt as a result of uneven substrate compression in the areas where piezoelectric energy harvesting devices are installed. The thickness of the asphalt layer likely has some indication of its lifetime and ability to endure wear. The substrate of the asphalt installation will be constructed of materials with variable stiffness ranges, and the impact of the varying substrate stiffness should also be investigated for

[24] Willoughby, Kim. Post Construction & Performance Report, Experimental Features WA 03-04, 04-01, and 05-04, Studded Tire Wear Resistance of PCC Pavements, Contract 6620 I-90 Argonne Road to Sullivan Road MP 286.91 to 292.38. Washington State Department of Transportation. 2007.

the roadway. For example, if the stiffness of the piezoelectric device is equal to the substrate, then no uneven wear would be expected. If the stiffness of the piezoelectric device is less than the substrate, then there may be an indentation forming above the device over time. If the stiffness of the piezoelectric device is greater than the substrate, then there may be indentations forming around (but not above) the device over time.

Appropriate weathering, wear, and tribology investigations should be conducted to examine the lifetime of the composite installation on both the asphalt and the piezoelectric devices.

Failure rates of the devices will have a direct impact on the system's ability to generate energy. **Decay mechanisms** in the piezoelectric materials themselves may reduce the output of the system. Presumably, the power or energy generated over time will be decreasing as the system has a cumulative increase in individual unit failures and degradation. An estimation of this failure rate would refine the LCOE calculation.

Finally, any **downtime** associated with maintenance or replacement should be considered, as this will also reduce the energy output and affect the return on investment. Downtime in the railway may have a direct impact on ridership, whereas downtime in the highway can increase labor costs and strain maintenance budgets.

Traffic Volume

As has been shown in all of the demonstration data so far, traffic volume has a direct relationship to the power generated for these devices. It has already been shown that the vehicle characteristics and vehicle weight greatly influence the performance of the system. The traffic model developed for this report should be validated by actual vehicle assessments in the event of a demonstration. Once confirmation of the power per module is obtained, the LCOE estimation techniques employed in this report can be revisited to reassess the required traffic characteristics to make the system viable.

Data in terms of vehicles per day or vehicles per hour is necessary in order to assess the cost effectiveness of the system. The traffic volume likely has an impact on the wear and tear of the system, so efforts to quantify this should also be considered. Traffic volume is directly proportional to the equivalent capacity factor of the system. The profile of traffic activity is also of importance as it will determine when the energy is available. If no energy storage is used, the timing of energy availability may be critical. Modeling the real LCOE with a variable traffic volume profile would be beneficial.

Vehicles on the roadway are free to change lanes at will, and are also able to vary their position within a lane to some degree. Therefore, there is some probability that when energy harvesters are implanted in the road, passing vehicles will not impart energy to the devices due to lane changes or asymmetrical positions within the lane. Therefore, there is a need to quantify what number of cars and trucks will actually contact the system when passing. A metric such as *number of cars per day* is likely greater than the number of cars that will actually produce energy.

In the railway application, virtually every passing train can ensure the harvesting of energy through the piezoelectric system. However, the optimum number of trains would need to be calculated to ensure an ROI.

Vehicle Speed

The duration of a vehicle tire impact with a bump in the road is audibly noticeable. Fast moving traffic creates a brief and loud report when tires hit a road imperfection, such as an expansion joint. Slow moving traffic creates a quieter report with a longer duration. The same is true for the impact of the piezoelectric devices. These devices have some extended surface area and length; a tire rolling over them is likely capable of producing energy over a fraction of that length. Therefore, there is some question to determine if a longer duration of energy transfer (slower vehicle speed) may create more wattage from the device. However, with decreasing vehicle speed, there is less kinetic energy that can be transferred to the device. Therefore, there is likely a trade-off between vehicle speed and power generated, and this should be determined. Such data would indicate whether the technology is better suited for highways, lower speed main arteries, or busy intersections.

For the Genziko product, the literature illustrates very high energy densities. It is not clear from the literature what the major functional components are in the technology, but it appears to be something similar to an array of cantilever piezoelectric materials that vibrate or resonate at frequencies associated with traffic or passing vehicles. This raises the question, however, concerning the suitability of this frequency range for all traffic patterns. If there is a dependence on vehicle speed for this technology, it may show that the device has very good energy density at only specific frequencies but low energy density at other frequencies (perhaps linked to vehicle speeds outside the best performance envelope). It is not clear whether this is a concern but this should be validated in a study.

As mentioned above, the railway application appears to have less dependence on train speed.

Installation Methods

The demonstration with Virginia Tech and the media produced by Innowattech have demonstrated that these systems can be installed by **a saw cut installation** (cutting or grinding sections of roadway approximately the width of a vehicle tire, installing the piezoelectric devices at a uniform spacing in the trench, connecting the devices and trenching the consolidated output to the roadside, encasing the array in concrete or epoxy, and repaving the installation in new asphalt). The **cost and downtime associated with this installation** should be investigated in more detail. In particular, if maintenance of the system is to be completed at regular intervals, this downtime should be incorporated into the lifetime energy production estimate (as it will also affect the LCOE).

It has been shown by Virginia Tech that the installation involves a saw cut in the road followed by chiseling to create a pocket into which the devices are installed. They are epoxied to the base of this installation, and the remaining area around them is filled with epoxy or concrete. Additional channels are cut to run wires to the side of the road. These are also filled with concrete. Asphalt can then be laid over the top of this installation.

The Genziko product is assumed to be installed in a similar fashion, with the exception of speed ramps which can be laid on top of a road structure for speed control and require little modification to the roadway.

The railway application appears to require much less installation labor than the roadway system and the devices can be installed above ground, between the rail and the rail tie. The units for the rail application are also smaller. Therefore, the cost of installation is likely less for railways than roadways.

Value of Additional Data and Avoided Inspection Costs

The piezoelectric system also provides a lot of information about road and traffic. This data may be possible to incorporate into existing monitoring and statistics systems needed by the Department of Transportation or traffic systems. The type and quality of the data should be evaluated to determine if there is added value which can be monetized in order to offset the cost of energy.

In addition, if this data provides a reduction in inspection costs, this may have value to the overall operation of the roadway. In the past, DNV KEMA has assessed the cost of SHM systems on wind turbine blades and found that avoided downtime – due to blade replacements and inspections – amounted to significant cost savings over the life of the system[25].

In the railway case, the energy generated from piezoelectric devices can provide data about the train weight since the voltage produced is a function of the force imparted on it. Overweight trains could be targeted and removed from service by the rail operator.

Energy Storage versus Net Metering

Generally, the system is presumed to cost less if energy storage is not required. The LCOE calculation does not separately parse out the costs of inverters or energy storage, but only estimates the cost based on quoted total installed costs. Present demonstrations imply that no energy storage was employed. Because the piezoelectric energy generation system is variable with road traffic, it is not unlike renewable energy systems in that its capacity factor may be low and its output may be intermittent. There are at least two, if not three, components for renewable energy systems that bring power to the grid. These components are an energy storage or energy conversion system (if desired), a direct current to alternating current (DC→AC) system which is typically handled by inverters, and finally, the output stage which is either constant output for a fixed time duration or it is *net metered*, meaning that the utility meter can spin backward or forward and therefore account for net energy production by subtracting produced energy from grid energy. These subsystems are described in more detail:

Energy Storage: The most common form of energy storage for renewable energy systems is lead acid batteries. Lead acid batteries are cost effective and are suitable for stationary storage, such as commercial or residential battery storage for solar PV installations. Lead acid energy storage systems are commonly seen for systems in the 0-100 kW range. Higher energy density batteries such as Li-ion, NiCd, and NaS batteries have been demonstrated, yet all have higher costs than lead acid. Appropriate evaluation of the energy storage technology – if required – is needed to measure the benefits of cost. Alternative energy conversion systems may be more complicated and could consist of electrolysis systems which produce hydrogen and then may be stored and later implemented into a fuel cell. These systems may be more complicated than batteries, but depending on the application, they may have advantages such as greater scalability or longer

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[25] Willoughby, Kim. Post Construction & Performance Report, Experimental Features WA 03-04, 04-01, and 05-04, Studded Tire Wear Resistance of PCC Pavements, Contract 6620 I-90 Argonne Road to Sullivan Road MP 286.91 to 292.38. Washington State Department of Transportation. 2007.

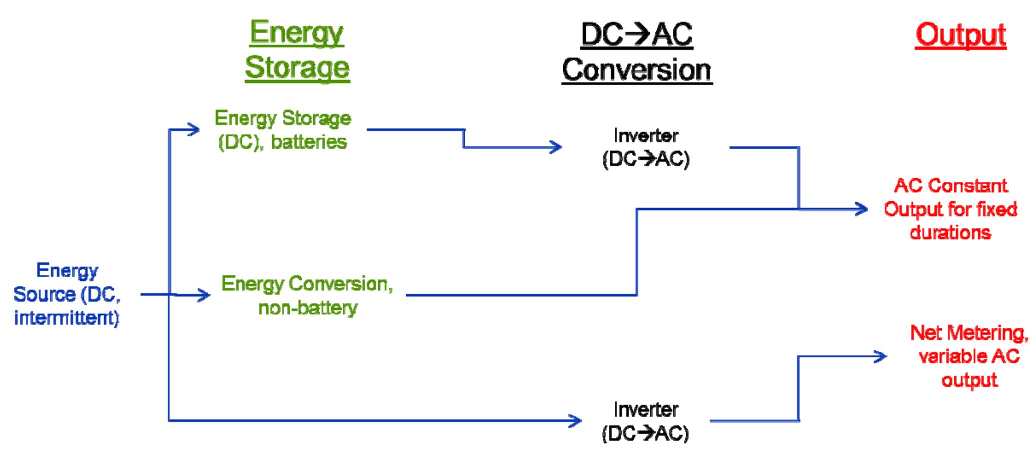
storage durations. As in the case of the batteries, **these systems require a cost and lifetime study** to evaluate the appropriate pairing of piezoelectric and energy storage systems.

Inverters: There are a wide range of inverters. Many are solid state devices and their cost is directly proportional to their power rating. There have been recent innovations in inverter technology such as the microinverters offered by Enphase which can attach directly to the back of individual solar panels. These low cost devices produce an AC power output directly from the panel and minimize the electrical connections needed to consolidate power output from a solar array. Since the United States grid operates with a 60 Hz alternating current, any DC source must be converted to 60 Hz AC at the appropriate voltage (usually 120 or 240 V). Innowattech has implied that a transformer has been designed to match the impedance of the energy harvester to the output system, and this transformer is more efficient in a railway application than roadway applications.

Output: The needs for the output depend on the required capacity factor and whether or not the system is grid connected. In a microgrid situation, there may be a need to store the energy so that it can be deployed at the right time. For example, if the roadway piezoelectric system is intended to power a dynamic billboard during rush hour, energy produced by the piezoelectric system can be stored in an appropriately sized battery and then the battery system can output energy for a few hours to power the billboard. Such a system would not need to be grid connected. However, if the billboard is intended to be visible all day, an energy storage system may be impractical and a net metering system may be more cost effective. If the billboard is metered on a single meter and the piezoelectric system can be connected to this meter, then the meter can be converted to a net metering system, and the energy consumed by the billboard can be offset by the piezoelectric energy generated.

Net metering is one of the most cost effective ways to implement renewable energy because it can bypass the cost of energy storage and directly account for produced energy by literally subtracting it from the energy meter reading.

Figure 33: Three Stages of Power Conditioning and Conversion to Deploy Intermittent DC Power Sources



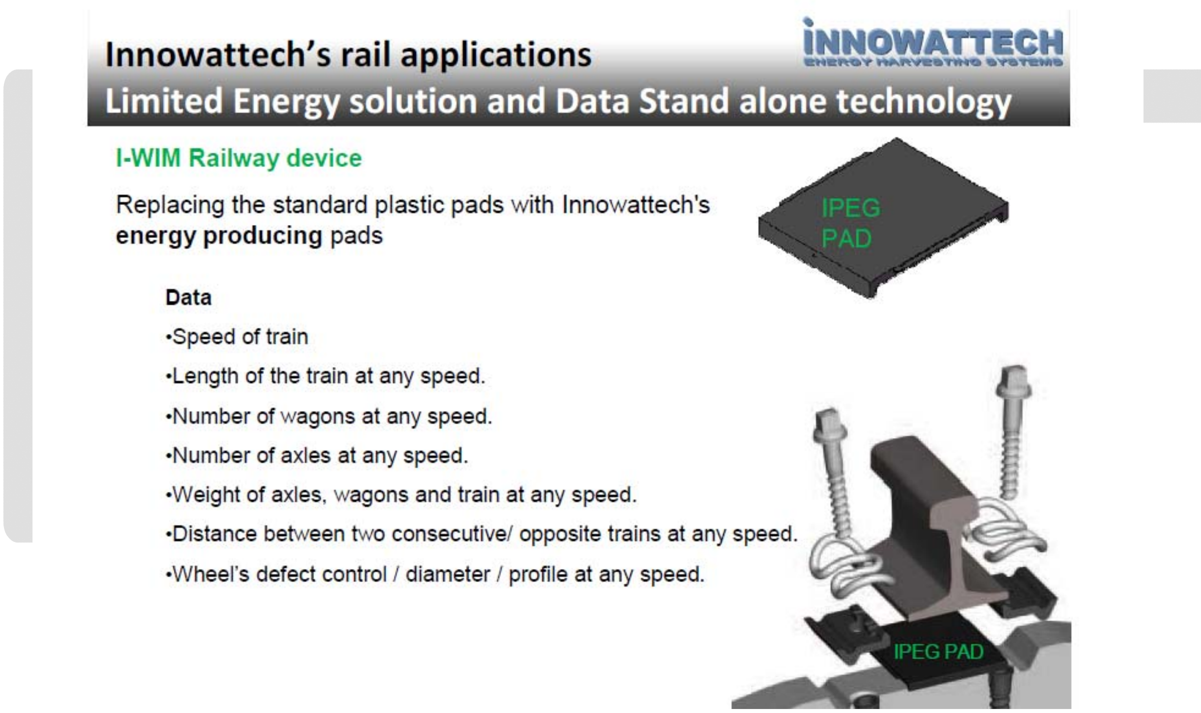
Source: DNV KEMA Energy and Sustainability

The deployment of the system should outline the requirements and costs of inverters and/or energy storage and should justify the appropriate end-use of the energy such that the system is optimized in the most cost effective fashion possible. The Genziko product explicitly illustrates that their system can be used with or without energy storage.

Appendix E:
Railways

Innowattech has some limited data on the use of piezoelectric materials for the purpose of harvesting vibration energy in railways. The technology appears to be incorporated into the track. There is also an indication of the device being incorporated into the railcars themselves, as shown in Figure 34. The general layout for the railway piezoelectric energy harvester is shown in "Roadways versus Railways" on page 39.

Figure 34: Innowattech's Rail Applications



One major innovation appears to be Innowattech's installation of railway devices with little or no interference or reconstruction required on the railway track (Figure 35). There is value added data from the Innowattech devices, such as the transformation of mechanical stresses into electrical output (voltage), which shall determine the number of wheels, weight of each wheel, the wheel's capitation and wheel perimeter position. In addition the speed of the train and the wheel diameter can be concluded via the fixed distance between pads. The energy is self supplied by the system[26].

[26] Innowattech Website. www.innowattech.com Accessed 1/3/2013.

Figure 35: Installation of Innowattech Devices on a Rail System

Appendix F:
Calculation Details

Compression-based Harvesters, Vendor Claims

Capital and cost of energy costs in Figure 17and Figure 18 were taken from the minimum, maximum, and average values of the NREL estimates[27].

The cost of energy calculation involves the following parameter with time dependence (Table 20).

Table 21: Explanation of Calculations for the Model

Parameter [unit]	Description	Calculation
Months [integer]	Time unit for model	The lifetime is determined by number of months or fraction of a year.
Construction or Maintenance Investment [$]	Costs incurred with the installation or replacement of the piezoelectric roadway system. The probabilistic value ($/km) is first incurred in the first month (Month 1). The next date when the cost is incurred will occur when the lifetime expires.	If lifetime trigger = true, then the replacement cost [$] = Cost per km [$/km] * number of kilometers [km]
Lifetime Trigger [conditional, integer]	Determines if the lifetime of the system has expired.	Generation of system = int (month/12). Expiration and replacement corresponds to the lifetime trigger increasing from one integer to the next.
kWh Generated [kWh]	Number of kWh harvested from roadway system per month. Assumes no energy is generated for the month of a replacement event.	24 hours per day * 30 days per month * claimed power generated [kW]
Energy Prices [$/kWh]	Uses energy prices from the Sacramento, CA region.	Assumes the energy prices are increasing over time at stated rate, for example, compounded. Price(n+1) = price(n)*(1+rate)
Energy Revenue [$]	Revenues earned by system due to energy generation	Energy Revenue [$] = Energy Prices ($/kWh) * kWh Generated [kWh]

[27] OpenEI: Open Energy Info. http://en.openei.org/wiki/Transparent_Cost_Database. Accessed January 1, 2012. National Renewable Energy Laboratory (NREL), Open Government Initiative, US Department of Energy.

Parameter [unit]	Description	Calculation
Year	Time in years	Month/12
Present Value of Investment [PV]	The present value of future costs and revenues.	(Installation and maintenance costs + Energy Revenues) / (1+discount rate/12)^year
Net Present Value	The discounted total of all investments and revenues at a future time according to the discount rate.	NPV(n) = sum(PV(0):PV(n))

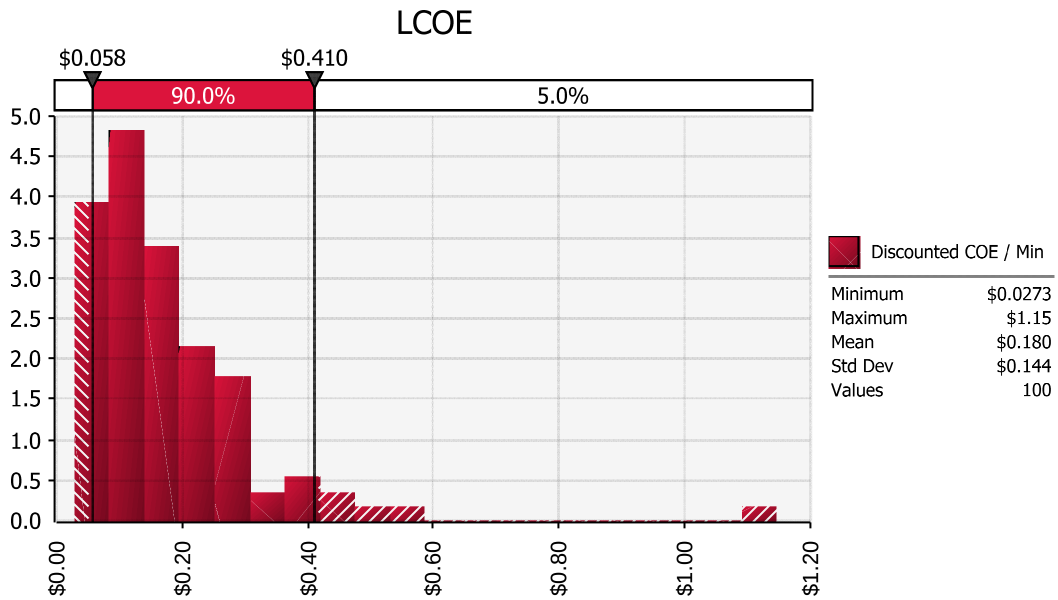
Case 1: Maximum Five Year Lifetime

It can be seen that the lifetime of the system is assumed to be between one to five years with a most likely lifetime of two years (Table 21). Presumably the system will last longer than this, however, the upper limit on the literature reviewed only demonstrates at a two-year lifetime thus far. Therefore, this is incorporated into the probabilistic estimation of the lifetime corresponding to a geometrical mean of 2.67 years. As a result, the LCOE is calculated to be $0.02/kWh at a minimum, and about $1.15/kWh at a maximum, with a mean of $0.18/kWh and a standard deviation of $0.14/kWh (Figure 36). The factors that most greatly affect the LCOE calculation are shown in Figure 36. The factors that most strongly lower the LCOE are the power generated and the lifetime. The factor that most increases the LCOE is the capital installation cost.

Table 22: Assumptions for the LCOE Model, Five Year Case

	Min	ML	Max	Dist
Discount Rate	0.05	0.06	0.1	0.07
Energy Inflation Rate	0	0.01	0.03	0.013333
Lifetime of Unit (y)	1	2	5	2.67

Figure 36: The LCOE including Discounted Present Value of Future Investments



Case 2: Maximum Ten Year Lifetime

It can be seen that the lifetime of the system is assumed to be between one to five years with a most likely lifetime of five years as shown in Table 22. Therefore, this is incorporated into the probabilistic estimation of the lifetime corresponding to a geometrical mean of 5.67 years. As a result, the LCOE is calculated to be $0.014/kWh at a minimum, and about $0.41/kWh at a maximum, with a mean of $0.08/kWh and a standard deviation of $0.05/kWh (Figure 37). The factors that most greatly affect the LCOE calculation are shown in Figure 38. As stated previously, the factors that most strongly lower the LCOE are the power generated and the lifetime. The factor that most increases the LCOE is the capital installation cost.

Table 23: Assumptions for the LCOE Model, Ten Year Case

	Min	ML	Max	Dist
Discount Rate	0.05	0.06	0.1	0.07
Energy Inflation Rate	0	0.01	0.03	0.013333
Lifetime of Unit (y)	2	5	10	5.67

Figure 37: The LCOE Including Discounted Present Value of Future Investments for the Ten Year Case

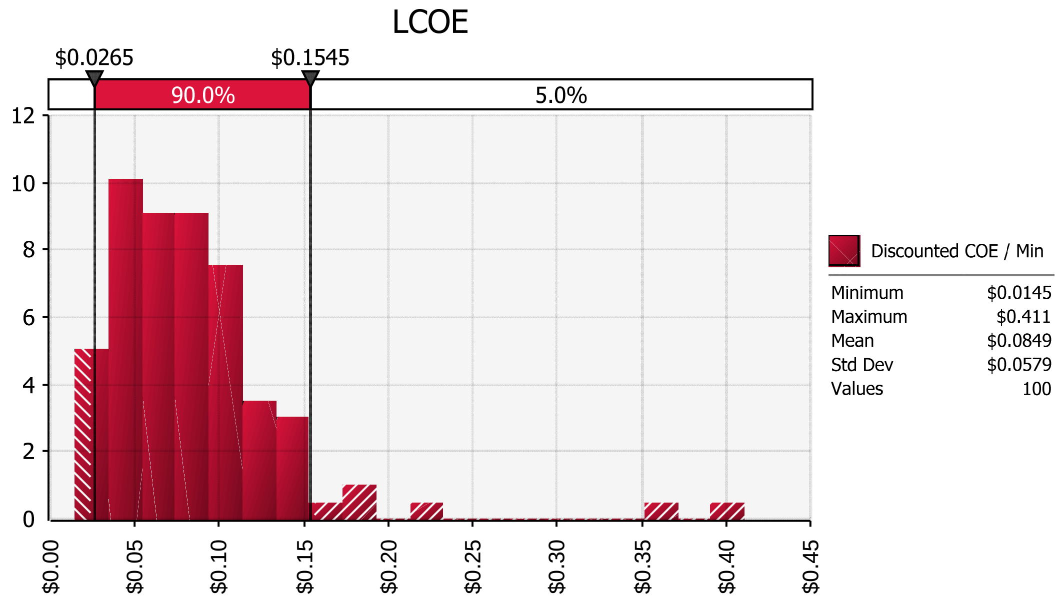
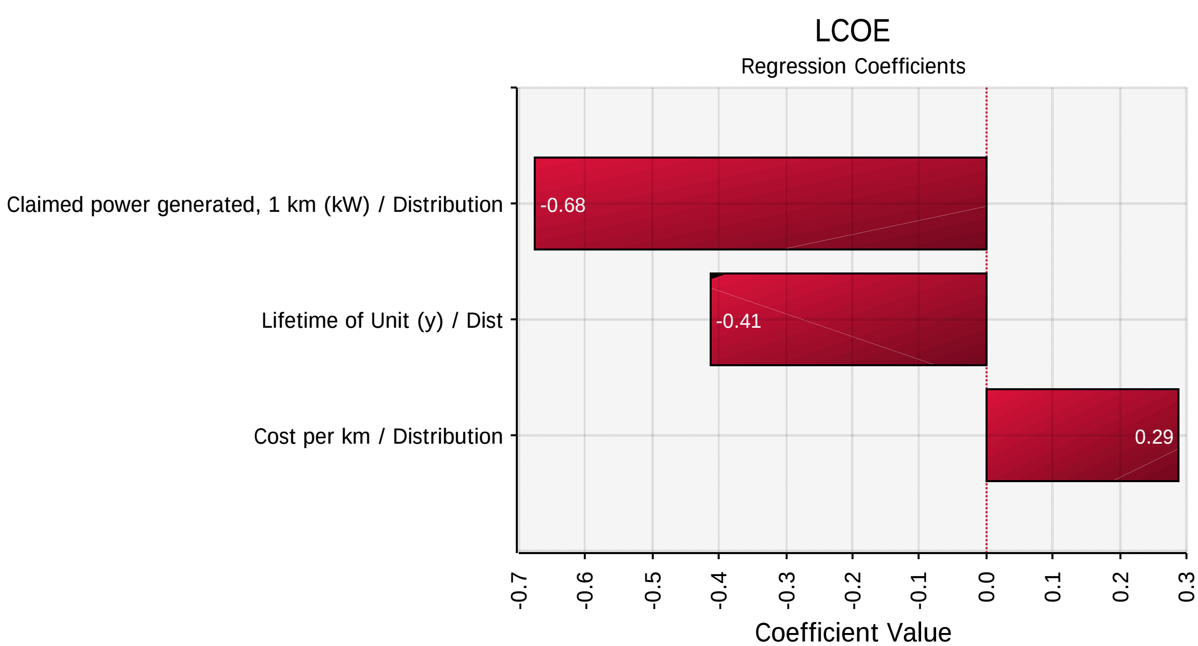


Figure 38: Sensitive Factors Affecting the LCOE for the Ten Year Case



Case 3: Maximum Thirty Year Lifetime

The thirty year lifetime case assumes a maximum lifetime of 30 years (Table 23) with a mean LCOE of $0.03/kWh with a standard deviation of $0.02/kWh (Figure 39). It can be seen that with an increase in lifetime, the cost of energy is significantly reduced, although the power generated and lifetime remain strong factors in reducing the cost of energy (Figure 40).

Table 24: Assumptions for the LCOE Model, Thirty Year Case

	Min	ML	Max	Dist
Discount Rate	0.05	0.06	0.1	0.07
Energy Inflation Rate	0	0.01	0.03	0.013333
Lifetime of Unit (y)	2	10	30	14.00

Figure 39: The LCOE Including Discounted Present Value of Future Investments for the Thirty Year Case

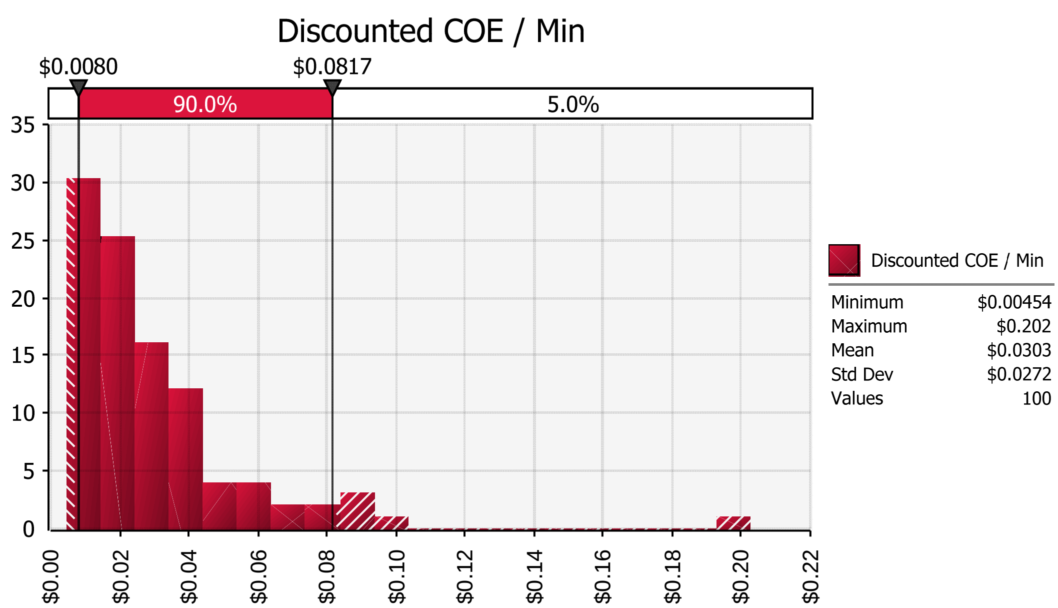
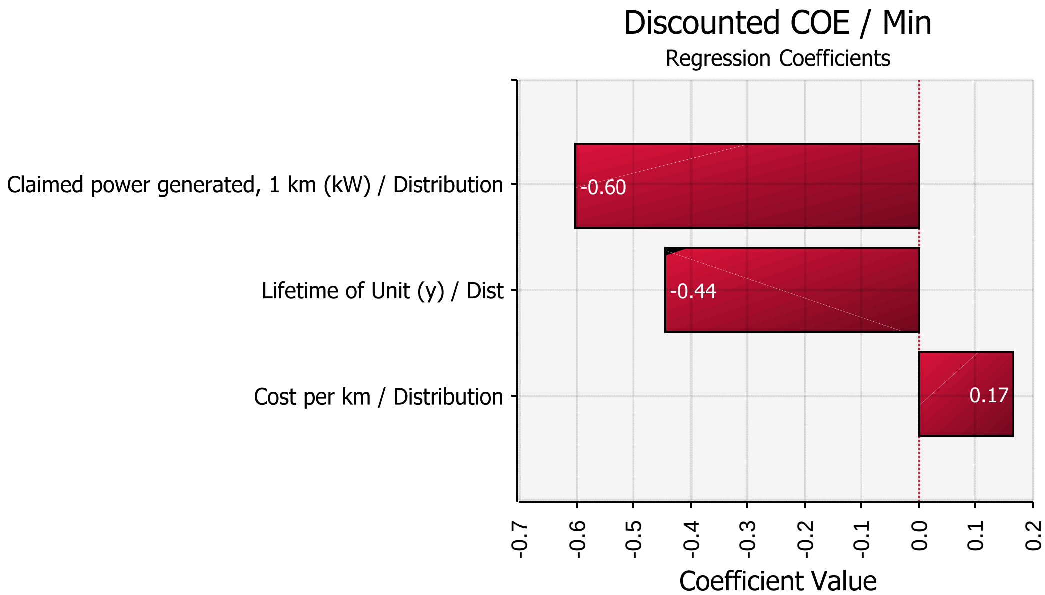


Figure 40: Sensitive Factors Affecting the LCOE for the Thirty Year Case



Traffic-based LCOE – Technology Agnostic

A model was constructed to disregard the vendor specifications for each technology and instead estimate the minimum energy density required in order to target a reasonable cost of energy. As a result, the model is a cross-checking mechanism. The inputs and calculations are as follows:

Table 25: Installation Metrics for the Generalized Case

Parameter	Value	Justification
Length of installation (km)	1	All examples work with a 1 km installation
Discount Rate	0.05-0.1	Averages to 0.07
Lifetime of Unit (y)	Variable	Same as previous cases – estimating 1-20 years.
Price for electricity sold ($/kWh)		
Wheel force multiplier	$4x10^{-6}$ - variable	This coefficient was taken from the line fit in Figure 9. It is the ratio for harvester power output to vehicle weight at the wheel. Assumes a linear relationship. This factor is **tuned** to estimate the LCOE and power output per module.
Energy Cost rate Increase	0.03	Assumes energy rates are increasing
harvester spacing (in)	8	Based on Innowattech dimensions, can be adjusted to fit footprint of Genziko

Parameter	Value	Justification
Cost per km	$650,000 or $27,000,000	Innowattech estimated $650,000/km. Using $2/W estimate from Genziko, $27,000,000 is the estimate for a 13.6 MW system
harvester pulse width (s)	0.1	Virginia Tech Demo
Vehicle Spacing Factor	Typically 0.05-0.07	Adjusted in order to calculate vehicles/hr

Table 26: Traffic Metrics for the Generalized Case

Parameter	Value	Justification
weight at vehicle wheel	Distribution	Ranges from 2200 – 58,500 N, based on variation across all vehicle types from Transportation Energy Data Book.
power per unit (W)	0.1 - variable	Virginia Tech demonstrated 0.08-0.14 W per unit. This value is a critical indicator of total system performance. This value can be varied to determine the minimum required power output to achieve a target LCOE (for example, $0.10/kWh)
speed (mph)	45-65	Variable ranging between 45-65 mph depending on conditions. In most cases a distribution assuming +/- 5 mph is assumed.
Wheelbase (ft)	Distribution, 11-13	Calculated from distribution of vehicles form Transportation Energy Data Book.
harvester pulse width (s)	0.1	From Virginia Tech demonstration – can also be tuned to investigate the impact on the model. For the Genziko product, values up to 1 s were assumed.
Energy Sale price ($/kWh)	$0.10 – variable, uncertain	Variable, using Sacramento, CA prices ranging from $0.09-0.15.
Number of axles	Distribution, 2-3	Distribution from traffic data, primarily 2 axles. Heavier vehicles increase average to nearly 3. This value determines time between hits.
Vehicle speed (fps)	~95	Convert mph to feet per second
Time between axle hits (s)	0.12	Vehicle wheelbase / feet per second
Time between Vehicles (s)	6 seconds (corresponds to 600 vehicles/hr)	3600 s per hr / vehicles per hr
Vehicles per day	14,656	Vehicles/hr * 24 hrs per day

Table 27: Calculated Metrics

Parameter	Value	Justification
Units per km	~9,800	2*1,000 m/km / harvester spacing (in m)
Nameplate capacity per km (kW)	Variable – dependent on wheel force multiplier	Units per km * power per unit
power per unit (W)	Based on wheel force multiplier, taken from the line fit in Figure 9.	Wheel force multiplier * weight at vehicle wheel
Capacity factor	Conditional – if time between vehicle hits is less than pulse duration, capacity factor is 1	Vehicle spacing factor * power pulse duration / time between vehicle hits
Vehicles/hr	Generally ~600	Vehicle spacing factor * 3,600 s/hr / (Number of axles/vehicle * s/axle hit)
Actual output per km (kW)	Variable – capacity factor dependent	Capacity factor * nameplate capacity per km
Simple COE	Based on time series calculation for 240 months (20 years)	Sum of all maintenance expenditures (lifetime expiration) divided by sum of all kWh produced
Discounted COE	Based on time series calculation for 240 months (20 years)	Sum of present value of all maintenance expenditures divided by sum of all kWh produced
50th Percentile NPV at 5 Years	Based on electricity sale price	Net present value of revenues – costs 60 months into the future
Capital Cost ($/kW)	Includes capacity factor	Cost per km / actual output per km
Cost per Harvester	Installed cost	Capital cost ($/kW) * actual power output (kW) / number of harvesters
Power Density (W/ft^2)	Estimate based on harvester spacing, which may include space between harvesters if they are not spaced end to end	Power per unit / (harvester spacing in square feet)^2

Parameter	Value	Justification
Installed Power Density (W/ft2)	Dependent on actual installed area	Actual output per km / (harvesters/km)* (harvester spacing)^2

Table 28: Time Series Metrics

Parameter	Description
Generated Energy per month (kWh/month)	Actual output per km (kW) * 24 h/day * 30 days/month
Value of Generated Energy	kWh/month * inflating Energy Sale Price $/kWh
Cumulative Value of Generated Energy	Revenue of previous month + revenue of current month
Construction or Maintenance Cost	If lifetime is expired, cost per km * number of km is subtracted from revenue for that month
Energy Prices	Inflating over time, compounded from energy price inflation rate
Cycle Fraction	Month number / lifetime in months. When this is an integer the lifetime is expired and a replacement cost is incurred. See *construction or maintenance cost* above
Cumulative P/L	Sum of this month's costs and revenues added to last month's costs and revenues since time = 0
Present Value	(Installation and maintenance costs + Energy Revenues) / (1+discount rate/12)^year
Net Present Value	NPV(n) = sum(PV(0):PV(n))

Figure 41: Approximated Triangular Probability Distribution of Traffic Wheel Weight using the Statistical Weight for Each Car Segment to Determine the Most Likely Average Vehicle Weight

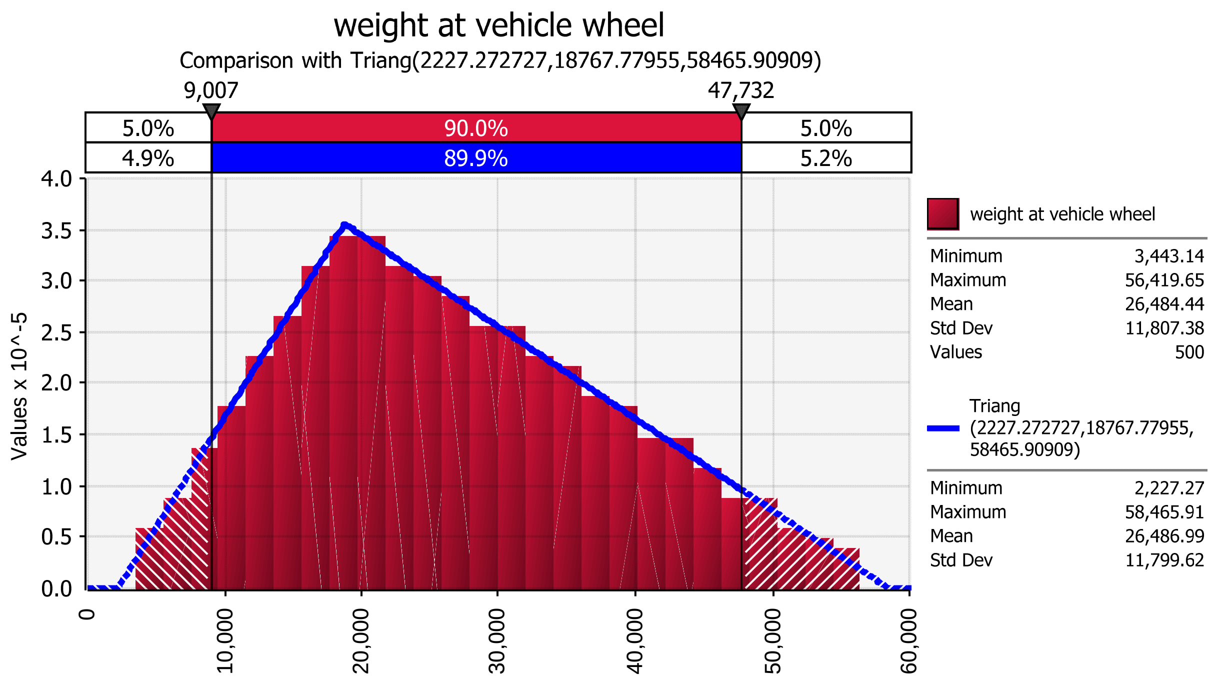


Figure 42: Capital costs with a Fixed LCOE of $0.11/kWh indicates a Tailing Distribution with a Maximum of $102,000/kW and a Mean of $14,391

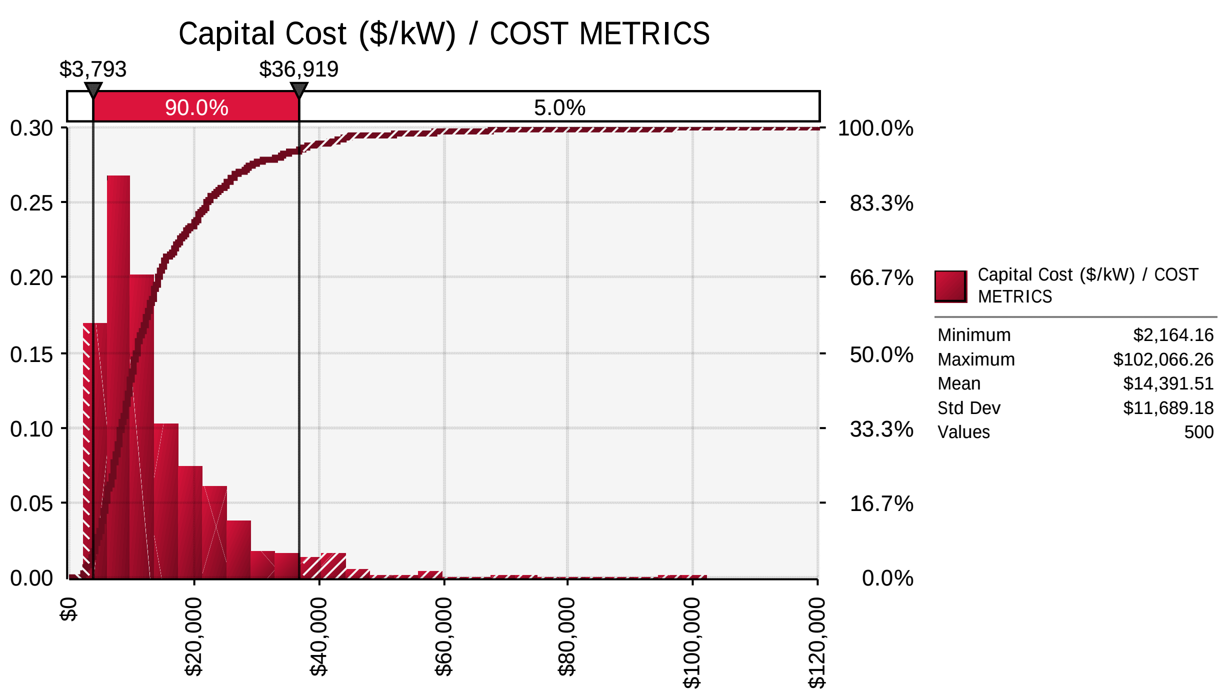


Figure 43: The Estimate of the LCOE with a Capital Cost of $4,000/kW Calculates 90 Percent of the Values to be less than $0.20/kWh

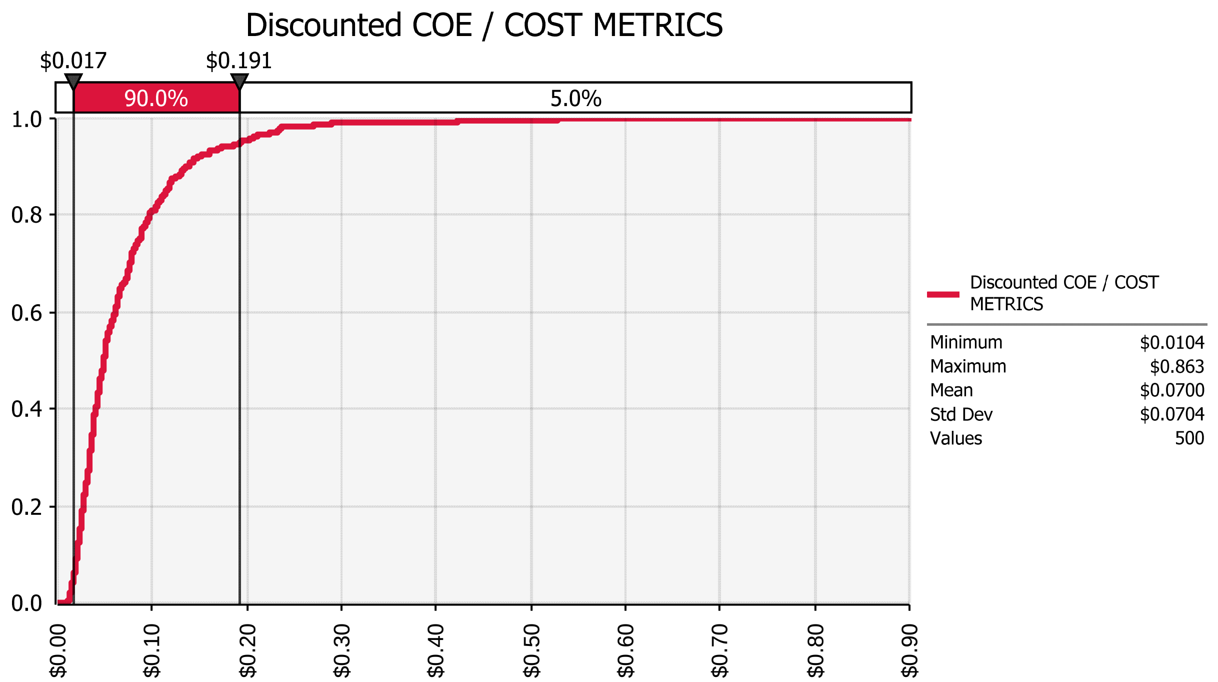


Figure 44: Weight at Vehicle Wheel and Harvester Pulse Width will Drive the LCOE if the Papital Cost is Fixed at $4,000/kW